# REPORT

on

# STUDIES OF STRATIFICATION IN MODERN SEDIMENTS AND IN LABORATORY EXPERIMENTS

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(Project Nonr 164(00), NR 081 123)

Office of Naval Research

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ILLUSTRATIONS

# INTRODUCTION

## Character of Investigation

The following report covers studies on the origin and genesis of cross-stratification in recent sediments, made by the writer in 1950, 51 and 52 with the aid of a grant from the Office of Naval Research (Nonr 164(00), NR 081 123). The investigation involved two phases: (1) a field study of original structures in selected representative environments including certain modern beaches, dunes, tidal flats, lagoons and alluvial fans, and (2) an experimental study of cross-stratification conducted in a delta tank in the department of geology laboratory at the University of Arizona. The experimental work was done with the capable assistance of Dr. George Williams during the winter of 1950 and 51, and of Mr. Charles Evensen during the spring and fall of 1952.

The field investigations described in this report are of areas considered typical of certain environments and in which stratification and cross-stratification have not to any appreciable extent been mixed with those of other environments. Furthermore, localities were selected in which the enterprises of man had not influenced the structures to be studied. Having selected the areas with care, the next step in the method employed was to dig trenches, oriented in various directions as required, in order to expose the stratification to view and to permit its study. Characteristic patterns of stratification were etched out through drying of the sediment or by other means and recorded in three dimensions. Limitations of time made impossible more than a sparse sampling of the many environments with which the study was concerned; so not more than a few reliable generalizations concerning these structures can yet be made. On the other hand, this marks a beginning of the systematic accumulation of data on the criteria for recognizing various environments as represented in ancient rocks.

The experimental work undertaken under this project was designed primarily to determine some of the controls, by changing one variable at a time, in the development of cross-stratification. Within certain limitations, which were largely those of the equipment and space available, satisfactory results were obtained. Experiments were necessarily restricted, however, to conditions of relatively slow currents of water, acting on a delta pool. No attempts were made to work with highly turbulent stream action or with wave motion. The results, therefore, must be recognized as applying only to one class of cross-stratification. With better equipment this type of study could be expanded profitably to cover numerous other varieties of structure.

## Value and Future of Investigations

The data and scale drawings on stratification assembled in this report constitute a record of modern sedimentary structures formed under known environmental conditions, useful for comparison with similar structures in ancient sedimentary strata. Information resulting from such comparisons is of value both (1) in ascertaining the type of environment of a past period and (2) in the practical work of correlating rock units, especially non-fossiliferous types, on the basis of comparable structures, i.e., the record of comparable environments.

An appraisal of the information at hand indicates that infinitely more remains to be obtained than is as yet available. Among the environments for which most data are available as beaches, dunes, and fans, additional samples are needed from many new localities, especially those which may prove to include additional types of structures. In the case of dunes, various forms such as the longitudinal and parabolic, the stratification patterns of which have not been recorded, need to be examined. Most important, however, are certain distinctive marine environments for which no detailed record of structures is yet available. Techniques for obtaining such data have not been developed to any great extent and numerous difficulties are involved; nevertheless, the information should be obtained to help the progress of stratigraphic studies.

With the advance of knowledge concerning the origin and environment of stratification in various deposits and with progress through the experimental approach, recognition of a third phase of the investigation becomes apparent. This phase consists of the study of ancient rock formations and includes an attempt to reconstruct their histories on the basis of stratification. It is not a new approach to the subject, for geologists have been attempting such reconstruction for over a hundred years. In the past, however, results have been only moderately successful, for they have not been based on a firm foundation of knowledge of present processes or of experimental data. Such formations as the Saint Peter sandstone, the Navajo sandstone and many others have been interpreted differently by different geologists. Clearly, more basic data are needed in order to critically analyze and correctly interpret many features of stratification.

## Classification and Terminology

The classification and terminology for stratification and cross-stratification as used in this report are those proposed recently by the author and Weir (McKee and Weir, 1952). According to this terminology, qualitative terms describing the character of rock layering are stratification, stratum, cross-stratification, cross-stratum, set, co-set, and composite-set (table 1). Quantitative terms applying to the thickness of stratification are very thick-bedded, thick-bedded, thin-bedded, very thin-bedded, laminated, and thinly-laminated (table 2).

The classification of cross-stratification used is based primarily on the lower bounding surface of a set of cross-strata. It includes three basic types: simple, planar, and trough. Features of secondary importance in this classification are (1) the shape of the set of cross-strata, (2) the attitude of the axis, (3) the symmetry of the cross-strata with respect to the axis, (4) the arching of the cross-strata, (5) the dip of the cross-strata, and (6) the length of individual cross-strata.

Table 1. Qualitative terminology for layered sediments

| | Horizontally stratified | Cross-stratified |
|---|---|---|
| Basic unit; single layer | stratum | cross-stratum |
| Group of strata (or cross-strata) in conformable series | set (of strata) | set (of cross-strata) |
| Layer composed of two or more sets | co-set | co-set |
| Layer compounded from strata and cross-strata | composite-set | |

Table 2. Quantitative terminology for layered sediments

| Stratification | | Cross-stratification | | Thickness |
|---|---|---|---|---|
| Very thick-bedded | | Very thickly cross-bedded | | Greater than 120 cm. |
| Thick-bedded | Beds | Thickly cross-bedded | Cross-beds | 120 cm. (about 4 ft.) to |
| Thin-bedded | | Thinly cross-bedded | | 60 cm. (about 2 ft.) to |
| Very thin-bedded | | Very thinly cross-bedded | | 5 cm. (about 2 in.) to |
| Laminated | Laminae | Cross-laminated | Cross-laminae | 1 cm. (about 1/2 in.) to |
| Thinly laminated | | Thinly cross-laminated | | 2 mm. (paper thin) or less |

## BEACH ENVIRONMENT

### Characteristics of beaches

A beach is defined (Beach Erosion Board, p. 4, 1938) as "the zone extending from the low water mark to the ... landward limit of effective wave action." It may be divided into a foreshore or part lying between the crest and the ordinary low water mark, and a backshore or part covered by water during exceptional storms only. The foreshore may be a smooth even surface or may be subdivided laterally by a series of cusps. The backshore may consist of one or more nearly horizontal surfaces called berms, formed landward from the beach crest. On the other hand, some beaches have no effective backshore development, but terminate at the bottoms of sea cliffs.

The physiographic form of a beach when it is buried and preserved as an ancient deposit is a feature that is especially distinctive. At any one time in its history, a beach is linear in shape; therefore, as a beach advances or retreats during the passage of time, it will form a thin sheet-like deposit. The only condition under which it could develop considerable thickness would be where the area of deposition was sinking at the exact rate of filling with sediments. Under such a situation, the beach would develop with length and thickness, but with little width; it would still be sheet-like in form.

Marine beaches are formed by the action of waves and of tides, but the effect of variation in the carrying power of waves normally is much more pronounced than modifications due to rise and fall of tides. Under usual marine conditions a lamina develops with uniform wave action in which a delicate balance exists between the deposition by the swash and erosion by the backwash. New laminae are formed or old ones destroyed with each change in the carrying power of the waves. Thus, beaches bordering open seas normally develop with a fine stratification in which each lamina represents the sorting of sediment during a particular condition of a constantly changing sea.

Stratification in beaches is distinctive because of the unique combination of factors that control its development. The foreshore deposits may be divided into two types--those of the upper foreshore which is the part of the beach extending from the crest to the zone of saturation and those of the lower foreshore which is the part within the zone of saturation.

Upper foreshore stratification in beaches of the California coast has been studied intensively by Thompson (1937, pp. 731-735) who has demonstrated that it is characterized by the development of even, uniform laminae that dip seaward at very low angles. Where the beaches are cusped and embayments have developed normal to the strand, certain variations in the directions of dip occur but the structure remains distinctive.

Deposits of the lower foreshore or zone of saturation have not been examined in detail, but apparently are very different from those of the upper foreshore. In many places these deposits form ridges or troughs (with axes parallel to the coast line), basins, small sand bars, tidal pools and other irregularities. In general, they are notably irregular as compared with features of the upper foreshore and the structures within them doubtless are correspondingly different. These structures include flat-lying, concentrations of shells or of micaceous detritus filling the basins and high-angle cross-strata, oriented in many directions, in the troughs.

Backshore deposits of beaches form a third distinctive group and the structures within them like those of the lower foreshore, are in strong contrast with those of the upper foreshore. Irregularities are characteristic of backshore deposits. In many places strata consist of thin, even, gently-dipping laminae like those of the upper foreshore, but most of them dip away from the sea; elsewhere they are developed in channels or troughs and consist of steeply-dipping and curving laminae or of shells and detritus that settled as horizontal beds in the depressions. Backshore deposits commonly merge into those of lagoons or of dunes.

## Beach at Corpus Christi, Texas

The beach on Mustang Island near Corpus Christi, Texas, was selected for examination because it represents a typical example of deposits developed on a low, flat coastal plain, bordered by a shallow sea. The beach, which extends in a northeast-southwest direction, was studied at a series of three "stations" (A, B, and C) located six miles apart along a twelve mile stretch of the island.

At low tide the foreshore beach is approximately 100 to 140 feet wide and its surface slopes seaward with a dip of two to five degrees. Upper limits of the foreshore beach are concealed in most places by small mounds of wind-drifted sand and these cover parts and, locally, all of the backshore beach (Fig. 1). At stations A and B the backshore slopes inland, with a dip as great as 2 degrees, beyond the area of wind-blown sand and it merges imperceptibly into lagoon deposits. At station C the mounds of drift sand that largely cover the backshore deposits, extend inland 160 feet, beyond where occurs an area of low dunes paralleling another of high dunes.

Sand on the beach at Mustang Island is very uniform and evenly grained. Analysis of a typical sample (Table 3) indicates that it is dominantly fine sand and has good sorting, according to the scale of Payne (over 90 per cent of the sample falls within two grade sizes). It is composed largely of quartz grains.

Table 3. Mechanical analysis of typical foreshore beach sand on Mustang Island near Corpus Christi.

| | V. coarse | Coarse | Medium | Fine | V. Fine | Silt & clay | Sorting |
|---|---|---|---|---|---|---|---|
| Grade per cent | .3 | .3 | 2.2 | 78.5 | 19.0 | .1 | Good |

At each of the three stations on Mustang Island, L-shaped trenches with depths of about two feet were dug in representative parts of the foreshore and backshore beaches. These trenches were so oriented that sections both parallel to and at right angles to the strand were exposed. Due to dampness of the sand, stratification was not at first apparent in these trenches, but as their walls dried, slight color differences and textural contrasts served to indicate the character of the layering.

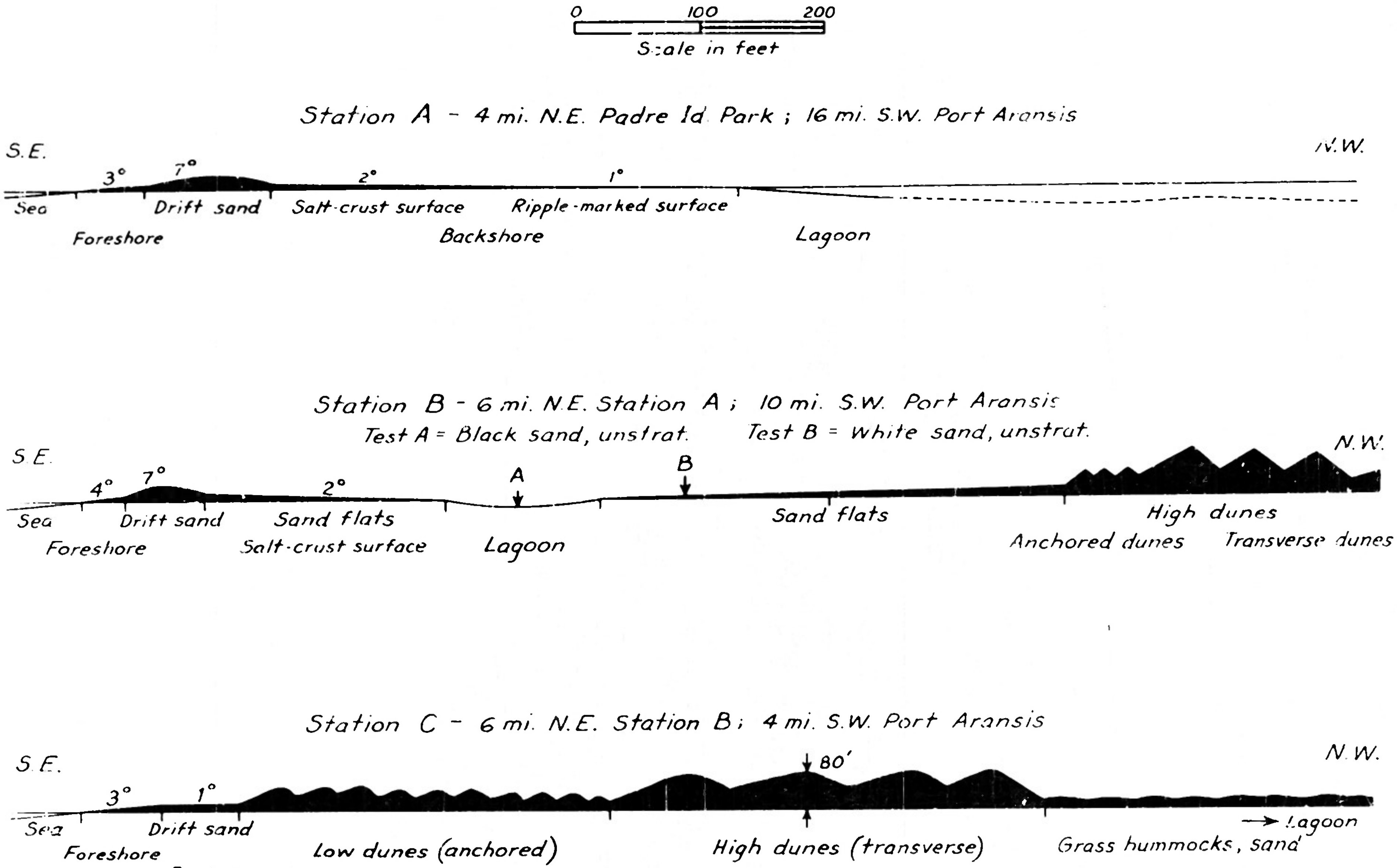

0
100
200
Scale in feet
Station A - 4 mi. N.E. Padre Id. Park ; 16 mi. S.W. Port Aransis
S.E.
N.W.
3°
7°
2°
1°
Sea
Drift sand
Salt-crust surface
Ripple-marked surface
Foreshore
Backshore
Lagoon
Station B - 6 mi. N.E. Station A ; 10 mi. S.W. Port Aransis
Test A = Black sand, unstrat.
Test B = White sand, unstrat.
S.E.
N.W.
4°
7°
2°
A
B
Sea
Drift sand
Sand flats
Foreshore
Salt-crust surface
Lagoon
Sand flats
High dunes
Anchored dunes
Transverse dunes
Station C - 6 mi. N.E. Station B ; 4 mi. S.W. Port Aransis
S.E.
N.W.
80'
3°
1°
Sea
Drift sand
Foreshore
Backshore
Low dunes (anchored)
High dunes (transverse)
Grass hummocks, sand
Lagoon

Fig. 1.

Upper foreshore deposits of the Mustang Island beach consist of strata that are regular, even, and have gentle slopes (Fig. 2; Plate I a, b). Sets of strata dip seaward up to five degrees and others dip similar amounts in directions parallel to the coast--the effect of large beach cusps that form ridges transverse to the strand at intervals of about 125 feet. All of the features of these beach structures such as the low angles and long, even surfaces likewise appear to be characteristic of upper foreshore deposits in other areas (Thompson, 1937, p. 731) and to be distinctive of this physiographic environment.

Backshore deposits of Mustang Island, in contrast with those of the upper foreshore, are characterized in most places by irregularities in stratification and, locally, by beds that dip at higher degrees (6-12 degrees). Debris, such as pieces of charcoal and layers of carbon, tends to destroy any semblance to evenness of bedding; local channeling and irregular erosion surfaces are typical features (Figs. 3, 4, 5).

## Beaches at Laguna and Oceanside, California

Beaches along the coast of California differ from those of the Texas coast primarily because they are built close to a mountain front and because their deposits slope off seaward at an angle that is generally higher than that in the Gulf of Mexico. One result of these differences is that the sand, being locally derived from wave-cut cliffs, contains a mixture of mineral types, and these are sorted by the waves into alternating light and dark laminae. A second result is that the dip of stratification of the foreshore beach ranges up to 10 degrees and commonly is 7 or 8 degrees, whereas on the Texas beaches it is mostly 5 degrees or less.

Stratification of the upper foreshore deposits on the California coast has been described in detail and illustrated by Thompson (1937, p. 731, Fig. 2). Records of upper foreshore beaches at Laguna and Oceanside made by the writer (Figs. 6, 7; Plate I d, e) emphasize the same features of stratification, namely the even, flat laminae, sets of which dip toward the sea with relatively low angles of varying degree. Laminae dipping in directions parallel to the shore doubtless also occur where beach cusps are developed, but they were not present in the deposits studied.

Backshore beaches are not present in many places along the California coast, for wave-cut cliffs commonly occur immediately back of the foreshore. Where backshore deposits are developed, however, they have a structure different from that of the upper foreshore. Although even and nearly flat lying in many places, the strata commonly dip away from the sea (Figs. 8, 9 10), and may dip at a relatively high angle (Figs. 8, 10). Especially distinctive of these deposits are the numerous troughs or channels, most of which are parallel to the coast (Figs. 8, 11, 12), and the many marked irregularities of erosion surfaces separating sets of laminae (Fig. 13).

An additional feature characteristic of and not uncommon among backshore deposits is intraformational conglomerate. Some beds of this are composed of unoriented chunks of laminated sand, broken from a parent deposit of unconsolidated sediment and redeposited nearby, in a matrix of similar sand (Fig. 14). Locally, concentrations of large shells or of charcoal and other unsorted debris are characteristic and, in places, clay beds are deposited among the sands.

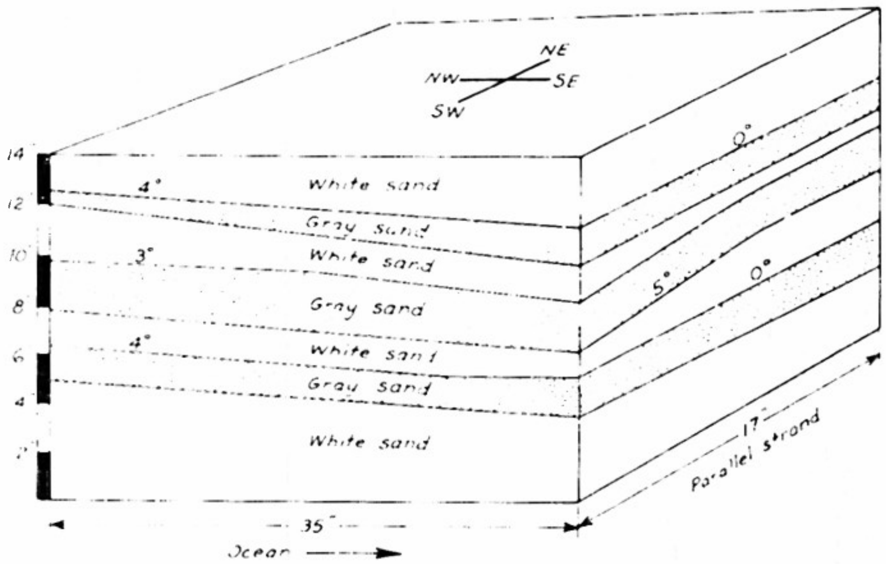



Fig. 2.

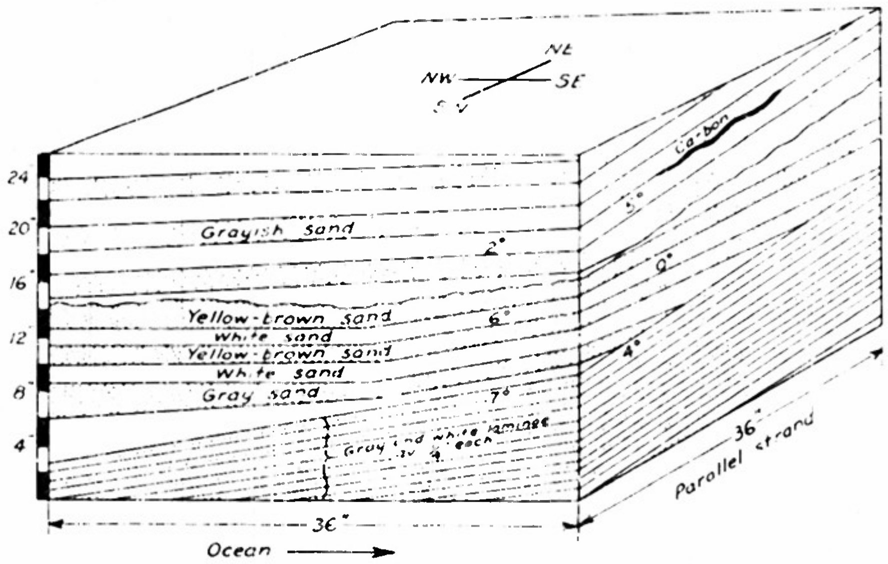



Fig. 3.

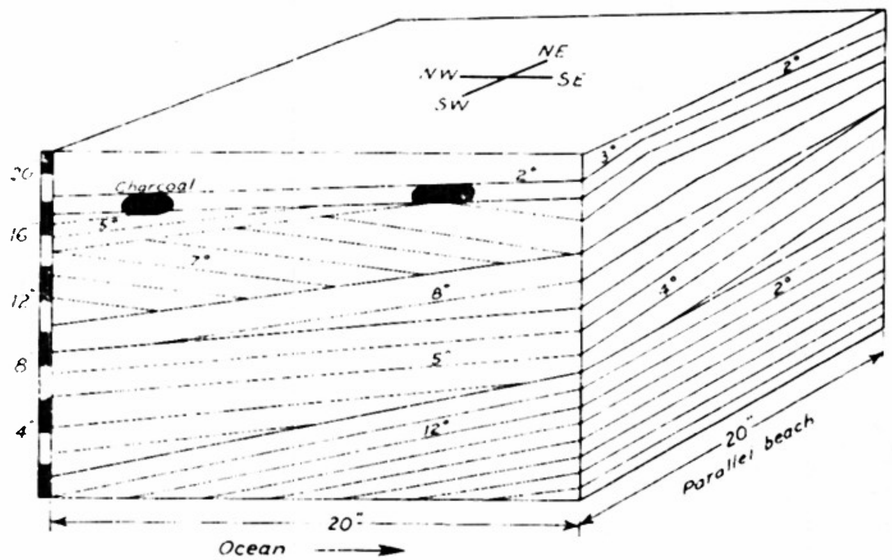



Fig. 4.

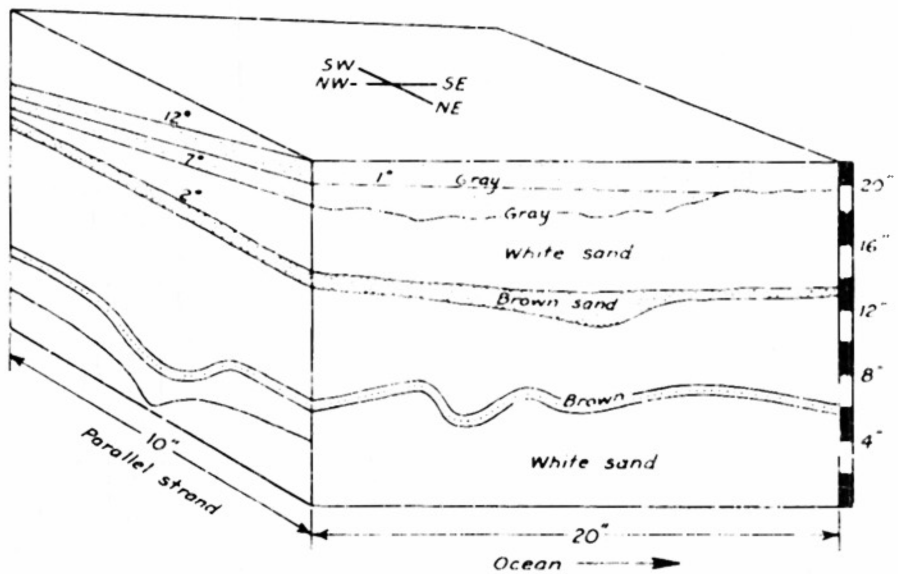



Fig. 5.

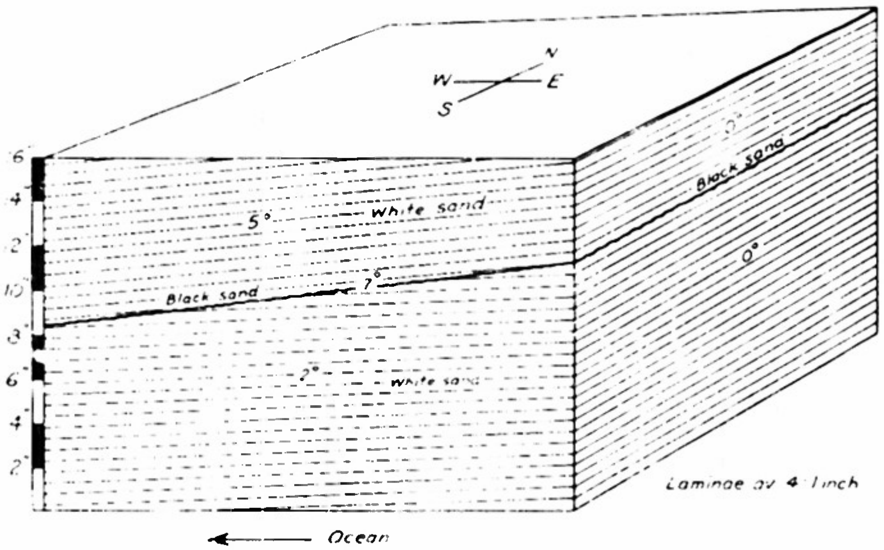



Fig. 6.

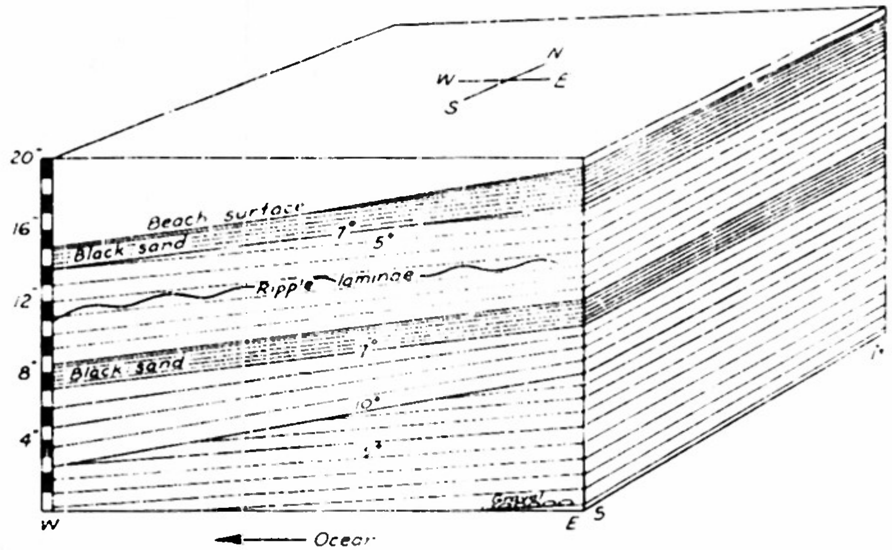



Fig. 7.

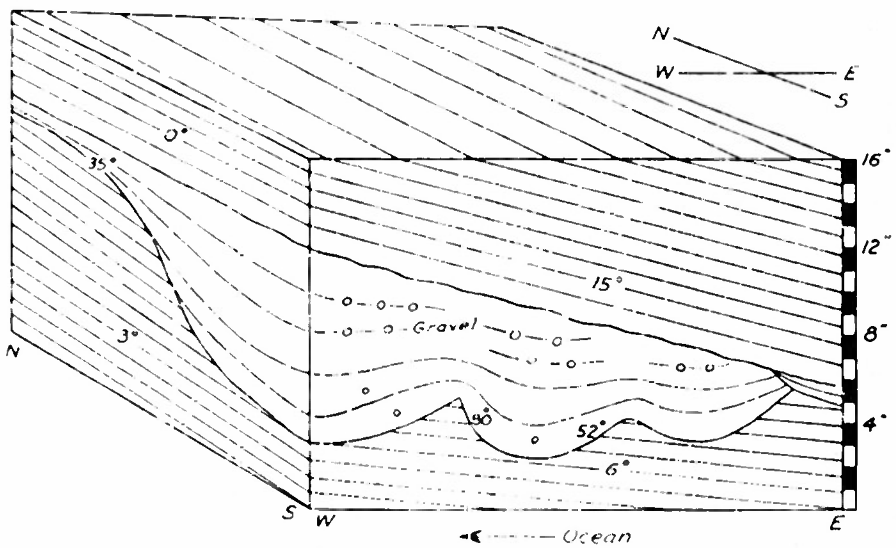



Fig. 8.

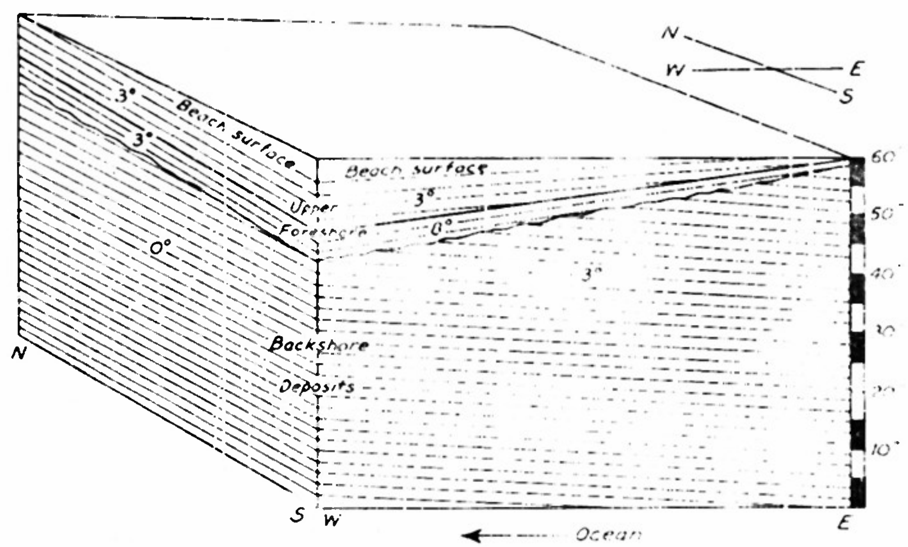



Fig. 9.

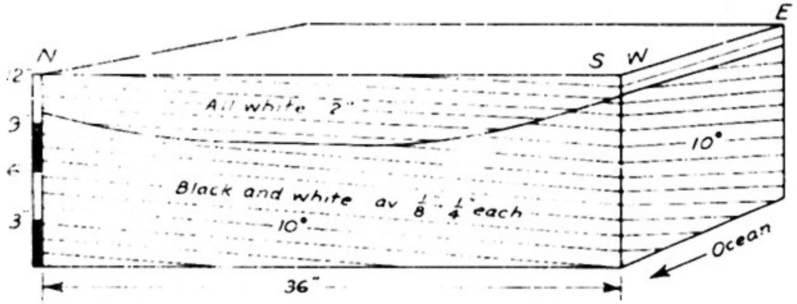



Fig. 10.

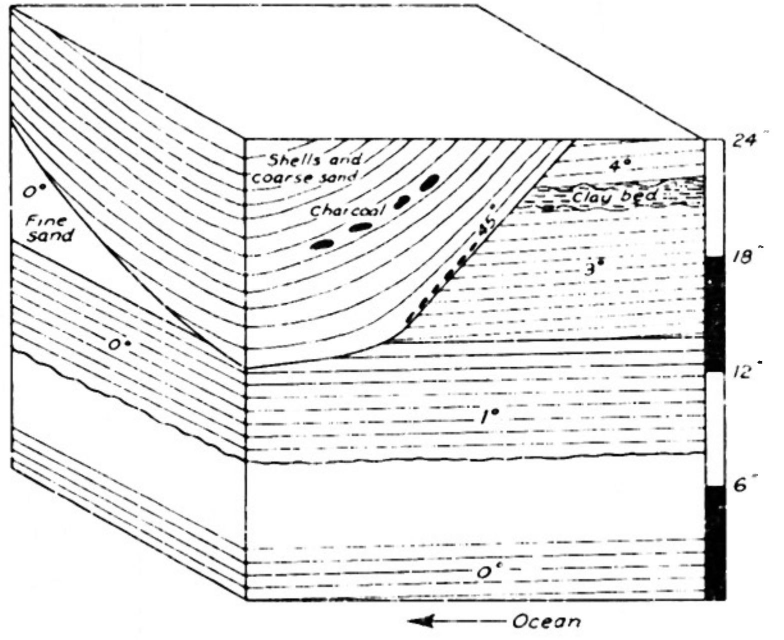



Fig. 11.

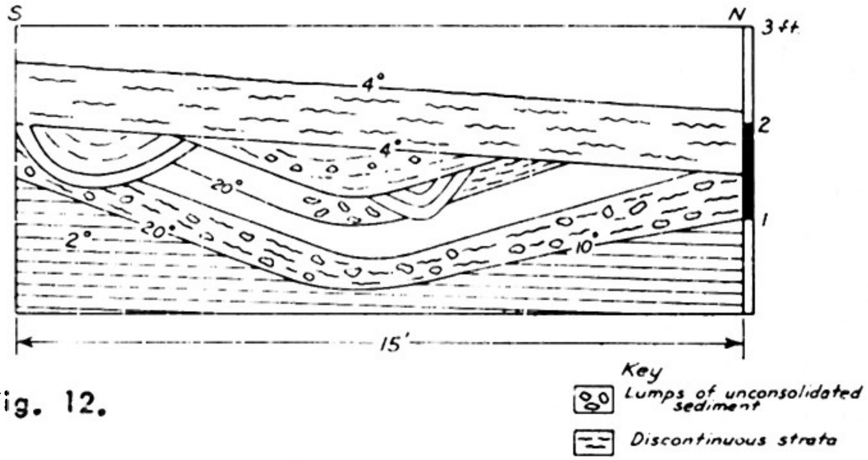



Fig. 12.

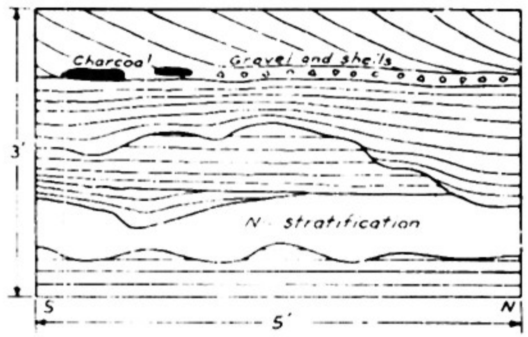



Fig. 13.

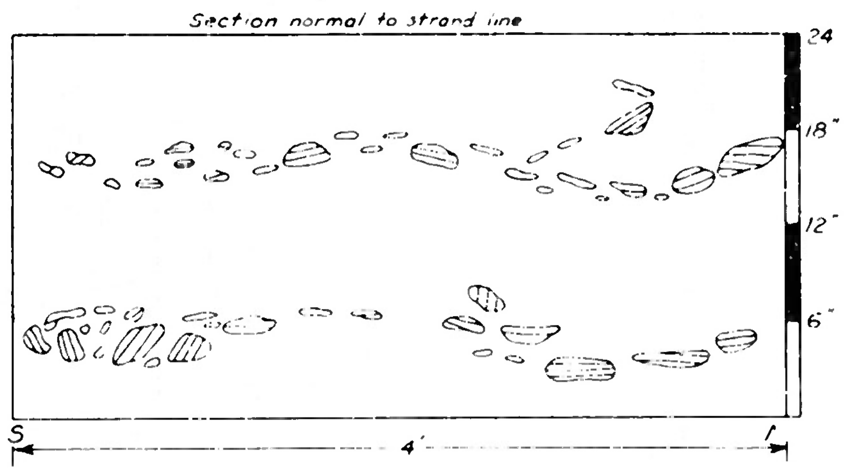



Fig. 14.

## Beach at Cholla Bay, Sonora

Bordering on both north and south sides of the tidal flats at Cholla Bay, northwest of Punta Penasco, Sonora, are beaches formed in part of coquina beds, some with unbroken shells and others entirely of shell fragments, and in part of sand derived from the crumbling of nearby granitic masses. The south beach is developed upon a granitic terrane and many of its deposits are supplied directly from hills and smaller outcrops of granite nearby; therefore, it contains coarse grains of granite minerals and even of the granite itself. In contrast, all of the sand on the north beach has undergone a considerable amount of transportation by tides and currents of the bay; so it is both finer and better sorted (Table 4).

At three places on the south beach, L-shaped trenches were dug in the deposits to determine the character of the stratification. One of these test trenches was in the southeast corner of the bay where the beach sloped up from a vegetation-covered lagoon toward an area of dune deposits. The other two were in the foreshore and backshore portions, respectively, of the south beach which separates the tidal deposits of the bay from a series of dunes. In all three of these deposits the poorness of sorting (Table 4) and the abundance of shell material of irregular shapes appear to be responsible for angles of dip (10-20 degrees) abnormally high for beach stratification. Probably also because of these factors which result from relatively little wave action, distinctive lamination such as occurs in most beach deposits is lacking and only crude layers, from one to several inches thick, are developed (Figs. 15, 16; Plate 1, c, Plate 2, b, c).

Table 4. Mechanical analyses of typical beach sands from Cholla Bay, Sonora

| | Percent shell frag. | Granule | Very coarse | Coarse | Medium | Fine | Very fine | Silt and clay |
|---|---|---|---|---|---|---|---|---|
| Foreshore, N. beach | 34.7 | 5.0 | 6.3 | 6.1 | 16.2 | 60.2 | 4.4 | 1.0 |
| Foreshore, S.E. beach | 30.1 | --- | 4.9 | 5.0 | 30.2 | 38.3 | 15.3 | 5.6 |
| Foreshore, S.E. beach | 29.8 | 25.3 | 30.6 | 17.5 | 10.5 | 6.1 | 5.7 | 3.3 |
| Foreshore, S. Beach | 42.7 | 24.6 | 61.0 | 12.3 | 2.0 | 1.0 | 0.6 | 0.3 |
| Foreshore, S. beach | 37.6 | 22.3 | 30.4 | 7.0 | 14.7 | 14.7 | 5.9 | 5.3 |
| Backshore, S. beach | 43.9 | 3.0 | 16.1 | 37.1 | 31.9 | 9.4 | 1.2 | 1.0 |
| Backshore, S. beach | 35.5 | --- | 0.1 | 9.3 | 64.2 | 21.3 | 2.7 | 0.1 |
| Backshore, S. beach | 47.9 | --- | 7.8 | 13.2 | 53.1 | 21.2 | 3.4 | 0.1 |

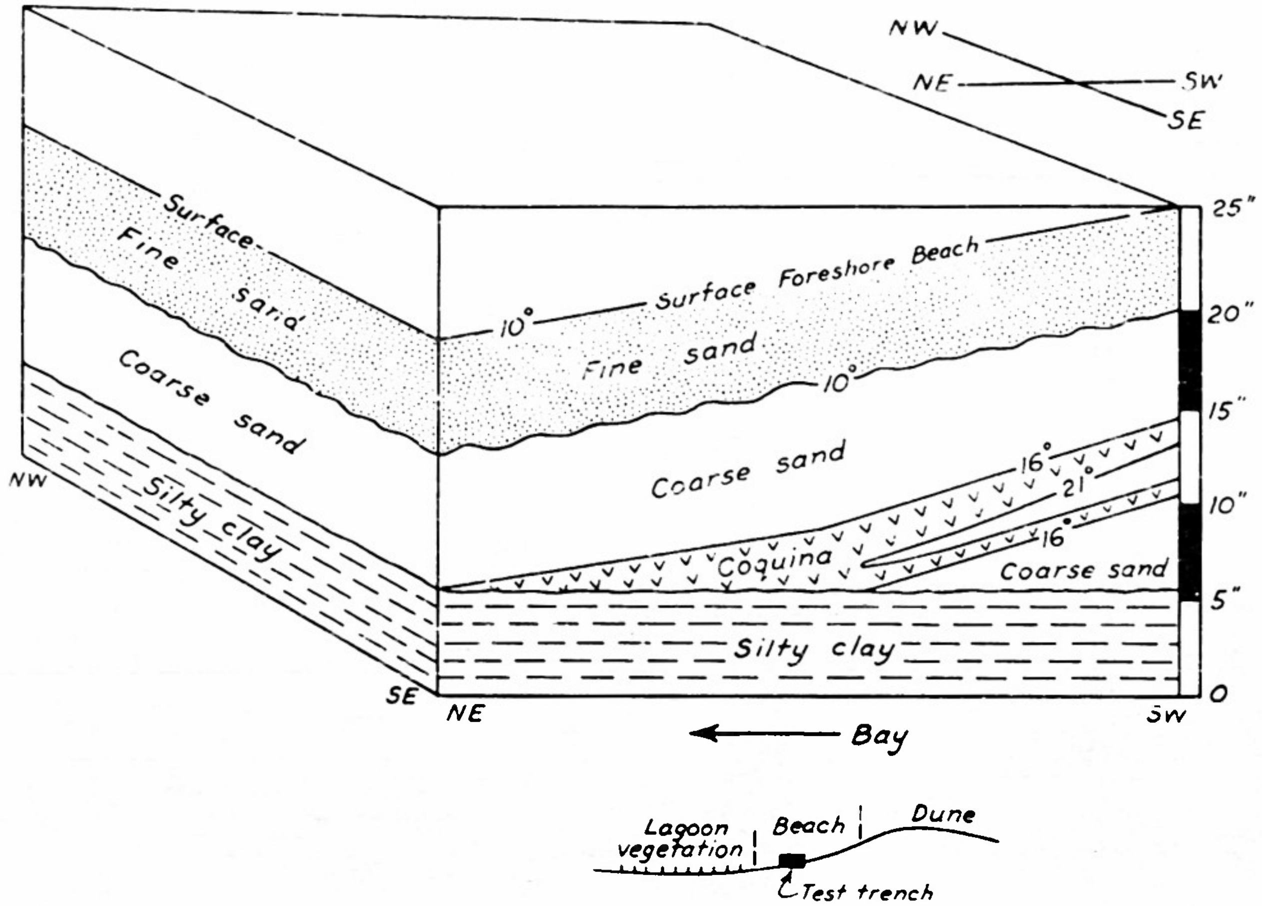



Fig. 15. - Beach bordering lagoon, SE corner Cholla Bay

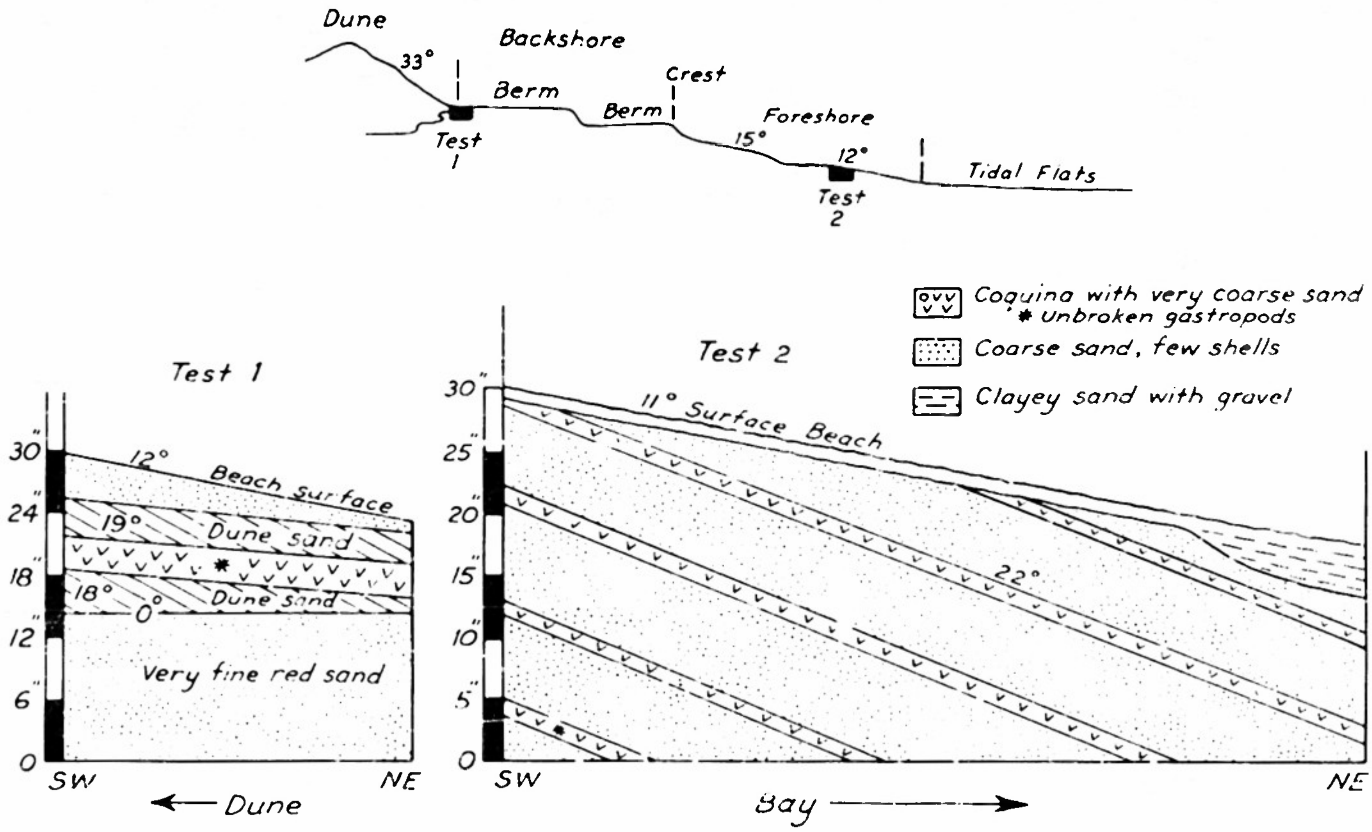



Fig. 16. - Cholla Bay, south side, 1/2 mi. s. of Lagoon

## Beach near Guaymas, Sonora

The beach on the west shore of Ensenada San Francisco, about twenty-five miles west of the port of Guaymas in Sonora, has been examined for stratification pattern. This beach differs markedly from those at Corpus Christi, Laguna and Oceanside in that it contains many beds or lenses of coarse detrital material and of large shell fragments (Table 5). In this respect it somewhat resembles the beaches at Cholla Bay, but it does not show effects of extensive tidal flats to seaward as in the latter.

Test trenches were located in three places on the beach at Ensenada San Francisco. One was in about the middle of the upper foreshore or 30 feet seaward from the beach crest. A second was at the beach crest so it exposed deposits of both foreshore and backshore. The third was on the inner margin of the backshore where it lapped over a small lagoon formed by its damming of a stream bed now dry.

Table 5. Mechanical analyses of typical beach sands from Ensenada San Francisco, near Guaymas, Sonora

| | Percent $CaCO_3$ | Granule & above | Very coarse | Coarse | Medium | Fine | Very fine | Silt & clay |
|---|---|---|---|---|---|---|---|---|
| Sandy gravel Foreshore beach (1) | 12.4 | 58.2 | 7.2 | 3.0 | 18.2 | 12.3 | 1.0 | 1.0 |
| White sand, Crest of Foreshore (2) | 23.2 | --- | 15.2 | 56.3 | 26.5 | 1.9 | 0.1 | .0 |
| Sandy gravel, Crest of Foreshore (2) | 17.8 | 70.5 | 16.2 | 9.6 | 3.6 | 0.1 | .0 | .0 |
| Black sand, shells Backshore-Lagoon (3) | 19.5 | 19.6 | 40.2 | 31.9 | 7.9 | 0.3 | 0.1 | .0 |
| Red sand Backshore-Lagoon (3) | 6.4 | 8.3 | 42.2 | 20.3 | 13.9 | 5.7 | 4.6 | 5.1 |
| Black sand; few shells. Estuary (5) | 16.6 | --- | 15.2 | 15.7 | 24.8 | 26.4 | 12.1 | 5.8 |
| Gray sand; many shells. Estuary (5) | 57.7 | --- | 26.3 | 16.9 | 28.6 | 28.2 | 2.1 | 0.2 |

Stratification of the upper foreshore is illustrated in test pits 1 and 2 (Figs. 17 and 18). The thick deposit of red brown clay in the bottom of test 1 appears to represent a basement of lagunal sediment across which the beach has developed. Similar clay forms the floors of lagoons that currently are to landward of the beach. The true foreshore deposits, therefore, consist of alternating layers of (1) gravels and shells and (2) relatively fine sand. The gravels are mostly 1/4 to 1 inch in diameter but some have 2 inch diameters. Most of them are of volcanic rock. The shells are unbroken in some strata but fragmental in others. Both flat gravels and shells are mostly oriented with short dimensions normal to the bedding. All of these deposits form irregular beds and lenses that dip seaward at low angles (4 to 6 degrees).

Backshore deposits are stratified as shown in test pits 2 and 3 (Figs. 18 and 19). Near the beach crest the strata are similar in composition and character to those of the upper foreshore, but they dip landward rather than toward the sea. On the inner margin of these deposits, however, they contain no gravels or other coarse material, but show evidence of having formed by finer sediments spilling over the beach margin on to the lagoon surface below. In these deposits (Fig. 19) the sand is sorted into laminae, composed alternately of coarse-grained, dark-colored and fine-grained, light-colored sediment. Shell concentrations also serve to make stratification prominent. Especially noteworthy are the relatively high angles (16-23 degrees) of dip among these backshore deposits.

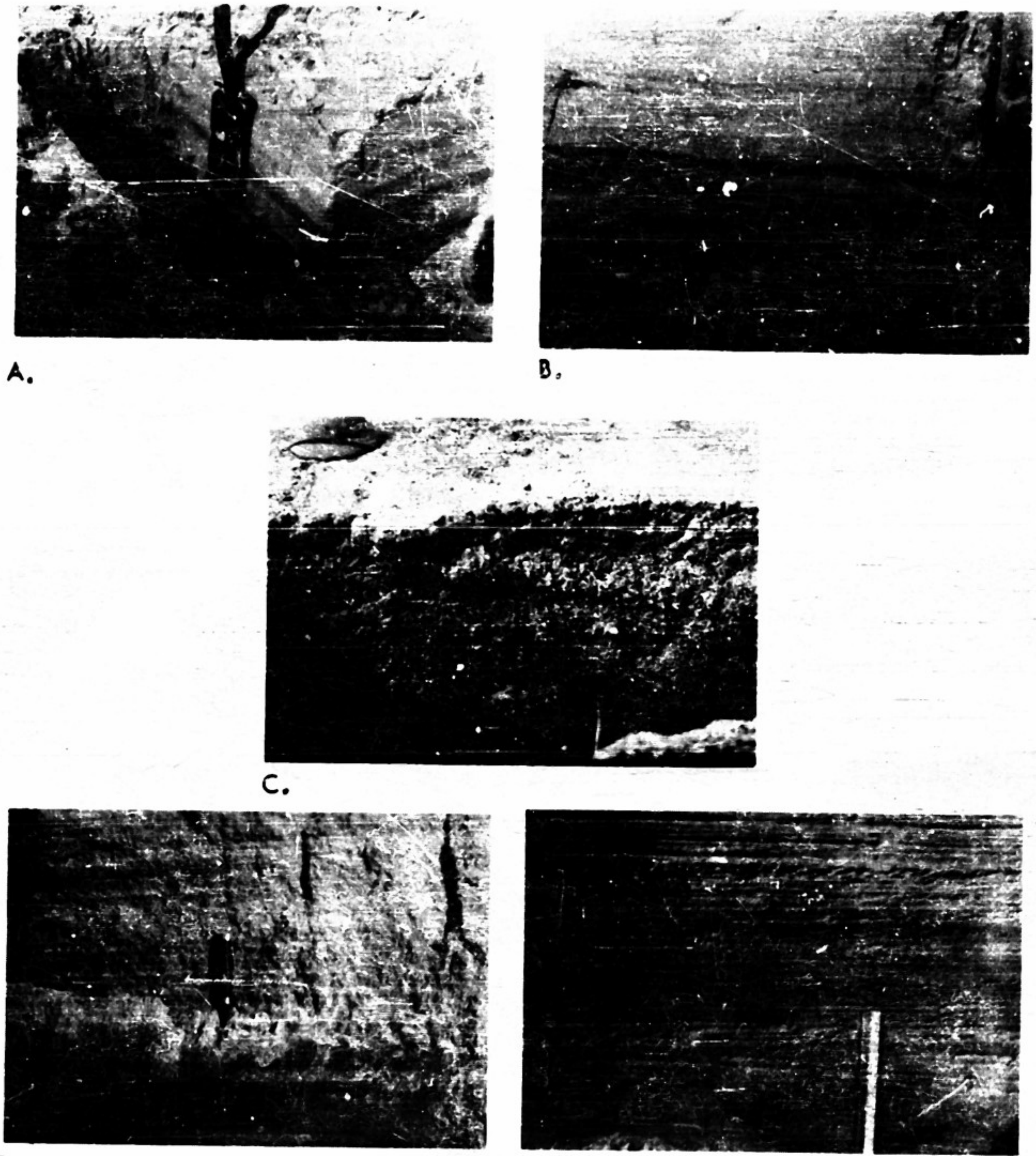



Plate I. - Beach stratification - Texas, Sonora and California

A. Mustang Is., Texas. Shovel in section normal to strand. Upper foreshore. Laminae show because of different rates of drying.

B. Mustang Is., Texas. Station D near Port Aransis. Section of upper foreshore normal to strand.

C. Cholla Bay, Sonora. South beach, normal to shore. Bay to right. Layering consists of shell fragments and coarse granite sand.

D. Laguna, Calif. Upper foreshore. Sea to left. Laminae due to alternations of light and dark minerals.

E. Laguna, Calif. Upper foreshore. Sea to right.


A.


B.


C.


D.

Plate II. - Beach and tidal flat stratification at Cholla Bay, Sonora. (Photos by T. Nichols).

A. Examining trench on south shore of bay.

B. Combination of types on backshore: (top) coarse sand and shell fragments, (2nd) truncated tongue of dune strata, (3rd) shell bed, (bottom) poorly sorted beach sand.

C. Foreshore beach. Bay to right. Strata due to alternations of shell layers and coarse granitic sand layers.

D. Tidal flat. Alternation of shell layers and beds of fine sand.

## SAND DUNE STRATIFICATION

### Characteristics of Sand Dunes

A dune, as defined by Bagnold (1943, p. 188), is a mound or hill of wind-deposited sand which arises to a single summit. The materials that form dunes are, with relatively few exceptions, similar. They consist dominantly of quartz sand, the grains of which range from about 1/16 mm. to 1 mm. (Udden, 1898) and in most areas are from 1/8 mm. to 1/2 mm. (Twenhofel, 1939). Sorting is good wherever sand has been extensively worked by the wind for, as stated by Shotton (1937, p. 540), "wind is by far the most efficient (agent) in sorting particles to a uniform size." Properties such as rounded-shape and frosted surface of grains tend to develop readily through wind action.

The forming of dunes involves a combination of two distinct processes. One is saltation or a bouncing movement by which wind causes sand grains to advance up the gentle windward slope of a dune. The other is avalanching or sliding by which, through repeated activity, masses of sand move forward and downward on the lee sides of dunes. Where saltation occurs the sand becomes ripple-marked and firmly packed. Where avalanching prevails, the sand is loosely packed but well sorted. In most areas only the avalanche deposits of the lee sides are permanently preserved, according to the findings of various investigators (Shotton, 1937; Bagnold, 1943; McKee, 1945).

Table 6. Degrees of dip on windward and lee sides of dunes as recorded by various investigaters.

| Reference | Windward slope | Lee-side slope |
|---|---|---|
| Beadnell, 1918 | 2.5-11 | 32-33 |
| Walther, 1924 | | 30 |
| Passarge (Quoted by Twenhofel, 1932) | 5-11 | 30-33 |
| Lahee, 1941 | 5-10 | 30 |
| Bagnold, 1943 | | 34 |
| McKee, 1945 | 12 | 32-33 |

Lee-side deposits of dunes differ from those of the windward side not only in being less densely packed, but also in forming much steeper slopes (Table 6). Individual layers in most dune deposits average 2 to 3 millimeters in thickness (Bagnold, 1943, p. 237-238) but may range from .05 to 4 inches in thickness, with lengths of individuals up to 50 feet and more (Thompson, 1937, p. 748). Various small scale structures such as slump marks of several types, ripple marks with crests and troughs oriented up and down the lee slope of the dune, and rain patches occur locally on surface deposits of the lee sides (McKee, 1945). In most dunes finest grains collect on the top and coarsest at the bottom of the lee-side slopes as a result of sorting during the avalanching process.

Numerous classifications of dune types have been proposed. Most of them are based on form which, in turn, reflects genesis. The classifications proposed by Hack (1941, p. 240-241) and by Bagnold (1943, p. 188-189) appear to be most acceptable because of their simplicity and applicability. Hack recognizes three primary dune forms: (1) transverse (including barchan), (2) parabolic and (3) longitudinal. Bagnold considers the barchan and the longitudinal to be the basic types.

Transverse dunes, as defined by Hack, range in size and shape from small crescents to extensive, elongate ridges, all of them oriented with crests at right angles to the wind direction and with outer margins or tails that point to leeward. These are formed, he believes, under conditions of little vegetation and abundant moving sand. The parabolic dunes include long scoop-shaped hollows and tails pointing to windward. They result from the tails being anchored by vegetation and the central areas forming "blowouts". Longitudinal dunes are long narrow ridges of sand that extend in a direction parallel to that of the prevailing wind and, as interpreted by Hack, result from a scarcity of vegetation, together with a scarcity of sand in motion. All three of these types, he believes, develop under conditions of a unidirectional wind and the particular type that develops in an area depends on the vegetation and available blow sand at any time (Hack, 1941, Fig. 19).

The two fundamental types of dunes, as recognized by Bagnold (1943, p. 189), are based on their relationship to the prevailing wind or winds. One of these--the barchan--is attributed to the action of wind from one dominant direction, and the other--the longitudinal--is considered by Bagnold to form where strong winds blow from a direction other than that of the general sand drift caused by more persistent gentle winds. Bagnold considers the transverse dune an unstable form and believes that it tends to break up into a row of "blow-outs" or dunes comparable to the parabolic dune of Hack. Thus, in his classification, the barchan, transverse and parabolic are all genetically related and do not warrant recognition as fundamental forms.

Basic types of dunes of both classifications appear to represent distinctive environments, despite the fact that Hack records his three fundamental forms in a single region--the Navajo country of Arizona. Longitudinal dunes observed by Hack were not active, so apparently developed in an earlier environment where conditions were different from those of the present. This dune form, as found in the North African deserts, according to Bagnold, occurs rarely if ever in the same geographical area as the transverse dunes. In Australia, only the longitudinal type is developed (Madigan, 1936, p. 205-227). Furthermore, the typical environments for developing parabolic and barchan dunes are not the same, for the parabolic type is the result of anchoring by vegetation, whereas barchans are favored by much sand and lack of vegetation. Because both are formed where there is only one dominant wind direction,

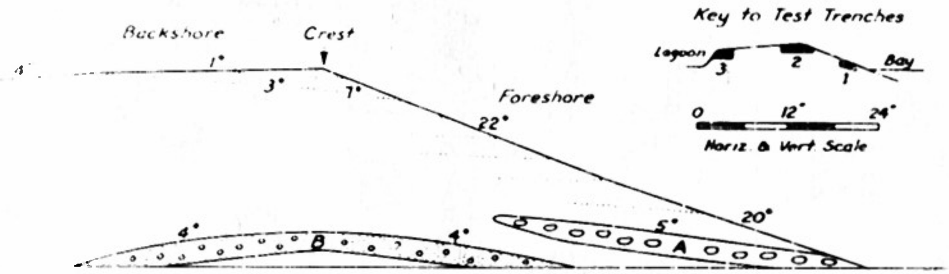



Fig. 17 - Upper foreshore, test trench 1, Ensenada San Francisco, 25 miles W. Guaymas, Sonora.

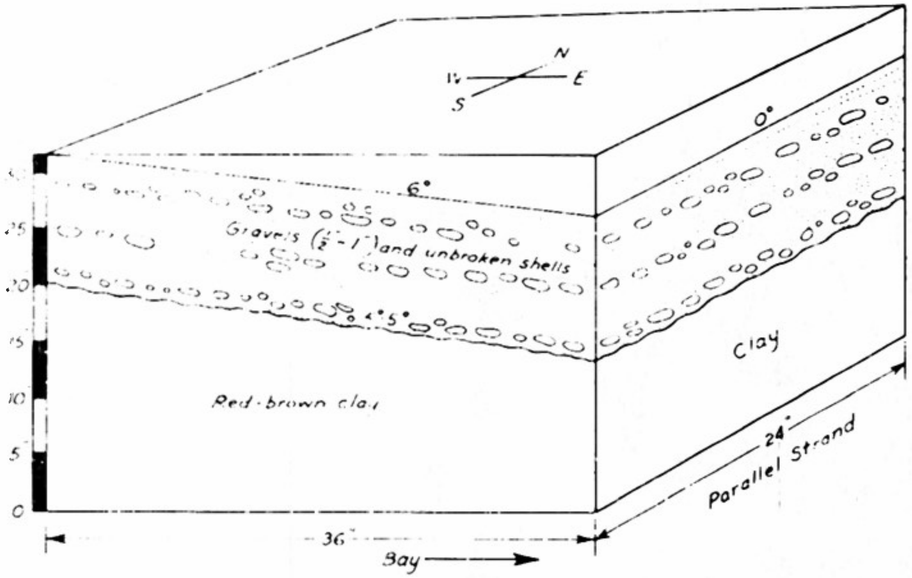



Fig. 18 - Beach at Ensenada San Francisco, test trench 2, 25 miles W. Guaymas, Sonora

A - Shells and flat gravels (1/4"-1") oriented parallel bed.
B - Broken shell fragments and granules (mostly dark volcanics), few rounded pebbles and shells.

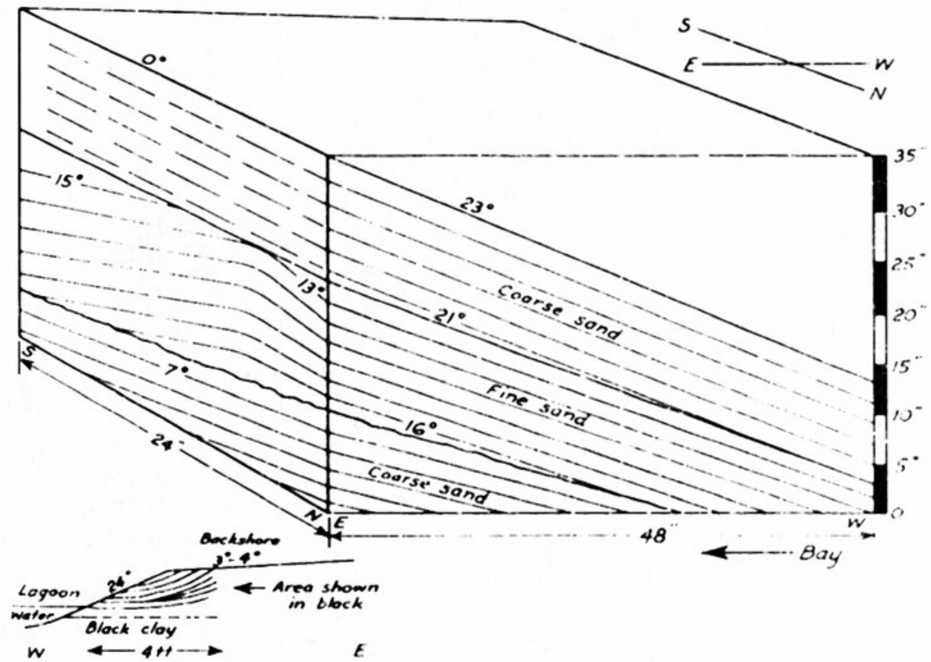



Fig. 19 - Back shore - Lagoon, Ensenada San Francisco, 25 miles W. Guaymas, Sonora (Laminae shown by shell concentrations and color contrasts)

however, they bear a relationship. In some regions, a transition from one type to the other is normal.

Most studies of sand dunes have involved texture, morphology or both. Few have dealt with the structures as represented by cross-stratification, doubtless largely because of the inherent difficulties of examining such features in the unstable sections of dry, friable sand. It has been stated (Walther, 1924, p. 281) that the morphological shape of dunes is the exterior expression of internal structure, suggesting that differently shaped dunes should have different structures. Little first-hand information on the subject is available, however, for few geologists have observed or recorded the stratification patterns on dune sections.

On a theoretical basis the structures developed in dunes such as the barchan or transverse and parabolic, that result from uni-directional winds, should have a high degree of regularity (Shotton, 1937). They probably consist of a preponderance of smooth, even-surfaced laminae with constant direction (Walther, 1924, p. 283; Bagnold, 1943, p. 240; McKee, 1945, p. 314, 325) as they are formed chiefly by the forward driving of the dune with lee-side slumping. Variations in lamination pattern result from (1) irregular slumping, (2) changes in wind strength and direction, (3) alternations of removal and deposition and (4) influences of vegetation. Despite many local changes, constancy of direction and type of stratification, and not an extreme irregularity as suggested in various texts, appears to be the distinctive feature of such dunes.

Concerning longitudinal dunes, even less is known of their structures from direct observation than in the case of uni-directional wind types. Because they are formed by winds from two directions, it may be supposed that they migrate through a process in which the steep, avalanche face shifts alternately from side to side as the wind changes direction. The resulting structure necessarily is more complicated than that of a transverse or barchan dune, but essentially similar in as much as individual portions formed under any one wind direction are concerned.

## Barchan Dune at Leupp, Arizona

A barchan dune located a few miles northeast of Leupp Trading Post, Arizona, was selected during the summer of 1951 for detailed examination. This dune was one of a large group that was unaffected by vegetation and had developed typical crescent shapes. It was composed of quartz sand, dominantly fine grained (Table 7) and with fair sorting (90% distributed through 3 grade sizes). The sand, which apparently was derived from the Triassic Moenkopi formation to the southwest, was very uniform throughout the dune.

The selected dune formed a double crescent with a maximum height of eleven feet on one side and eight feet on the other. The dip of the windward slope ranged from five to seven degrees and that of the lee side below the crest was 31 to 32 degrees. The width of the combined crescents was about 270 feet (Fig. 20). The dune crest was oriented normal to the direction of dominant wind which was N 30°E.

For the purpose of determining the structure of the dune a "seepage method", suggested by Bagnold (1943, p. 238, 244), was used.* Water from a tank was poured into

* The assistance of Dr. John Harshbarger, C. A. Repening, Erich Blissenbach and Milton Wetherill in dissecting the dune is acknowledged with thanks. Some of the photographs are by Blissenbach.

an artificial basin placed at the crest of the dune and from the basin allowed to penetrate the sand as rapidly as possible. Thus the water spread outward and downward following planes of stratification. In the course of a few hours it had saturated the dune to the depth of some feet in all directions, making possible with the aid of a shovel the sectioning of the dune to show vertical faces. Later, as the walls of wet sand that were exposed in the trenches began to dry, stratification due to differences in texture became visible and its pattern was recorded.

Essential features of the structure in this barchan dune are shown in a series of sections (Figs. 20, 21). Section one is located on the crest of the east crescent; section two on the ridge between the crest and the east wing; three, four, and five on the wings; six, seven, eight and nine on the gentle slope of the windward side.

The outstanding characteristic of the stratification is its general uniformity. Except on the wings there is little divergence from what may be considered a dominant trend in direction and dip of cross-strata.

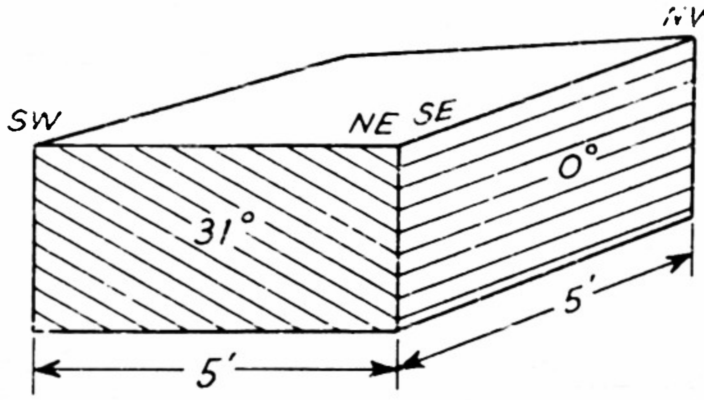
Table 7. Grade distribution in sand of barchan dune near Leupp, Arizona

| Location | Very Coarse | Coarse | Medium | Fine | Very Fine | Silt & Cl |
|---|---|---|---|---|---|---|
| Center crest of east barchan | 0.0 | 0.1 | 20.9 | 63.2 | 12.9 | 0.8 |
| Swale between dune crests | 0.1 | 0.4 | 14.1 | 66.5 | 18.6 | 0.6 |
| East wing | 0.1 | 0.3 | 22.1 | 63.1 | 13.9 | 0.9 |
| West wing | 0.1 | 0.7 | 23.0 | 57.7 | 17.2 | 1.1 |

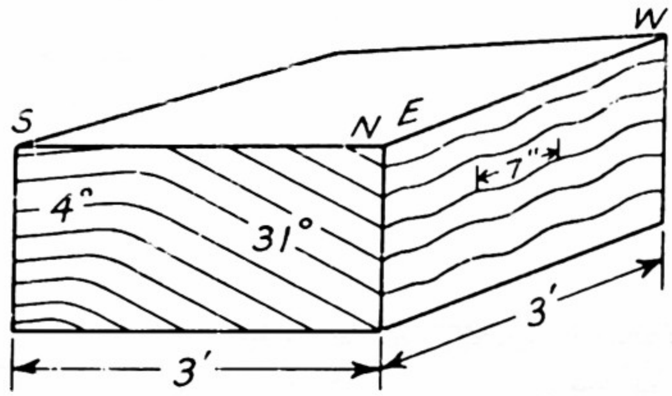
The section on the dune crest (Fig. 20 a; Plate III c, e) and others at intervals down the windward slope (Fig. 21; Plate III a) all show long even laminae dipping consistently 31 to 32 degrees in the direction of wind movement. An exception to this trend is on the lower part of the windward slope where bevelled tops of these strata are covered by a thin veneer (2 inches thick at 12 feet above base; less farther up slope) of laminae dipping in the opposite direction (upwind) at eight or nine degrees. Higher on the dune only the strata dipping steeply to windward are preserved even at the surface.

Section 2, on the ridge midway between the crest and wing end, shows a series of long, even laminae sloping at 31 degrees to lee (Fig. 20b) like those in the barchan center. In section 2, however, the laminae do not have truncated tops but form continuous curves over the ridge area to where they dip 4 degrees in the opposite direction (to windward). In a direction parallel to the dune ridge, these strata show another feature of significance. Lines of stratification appear essentially horizontal and parallel, but have wavy surfaces (Fig. 20b; Plate III d). Such irregularities are the result of small local slumps that have, in this area, kept the steep lee-face of the dune from having a smooth, even surface. They have an effect on dune stratification comparable to that of cusps on beach stratification.

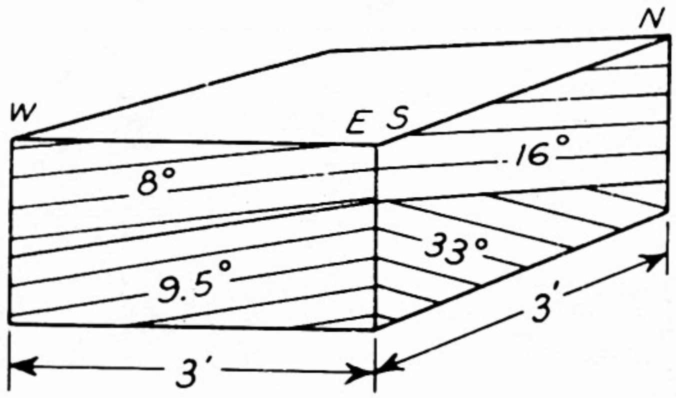
On the wings of the barchan are the greatest variations from a normal trend in stratification. This is because (1) the wings represent positions of least wind-current stability, (2) they are located where an extreme is developed in orientation of the avalanche face and in height of dune ridge. Sections cut on the easternmost wing to show structures in three dimensions (Fig. 20c; Plate III b), include on one face a set of strate sloping at 35°, which has been bevelled and covered by another set of strata sloping at 16°. Similar variations, representing changes in direction and amount of dip, are shown in sections on the westernmost wing (Figs. 20d and e) and apparently are characteristic of this part of the barchan. Also typical of stratification on the wings is the relatively low angle of dip developed in many strata that slope down in the general direction of wind movement.



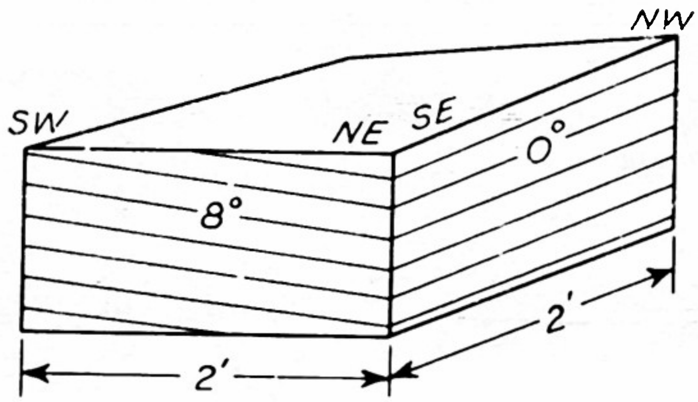

A. Section 1. Crest on east side



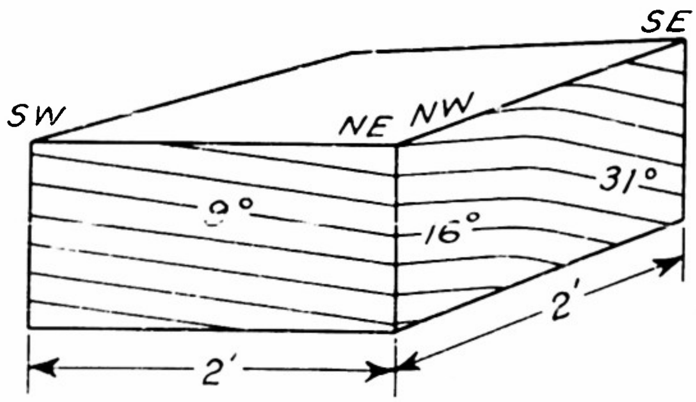

B. Section 2. Ridge 16 ft. se. of crest



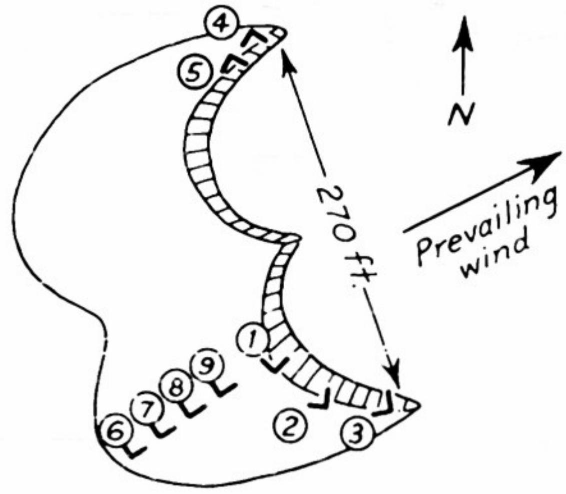

C. Section 3. Near end of east wing




D. Section 4. Near end of west wing

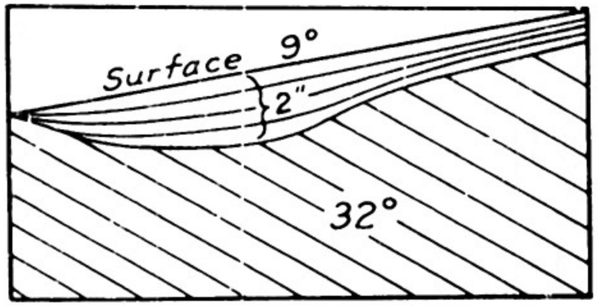



E. Section 5. Near end of west wing

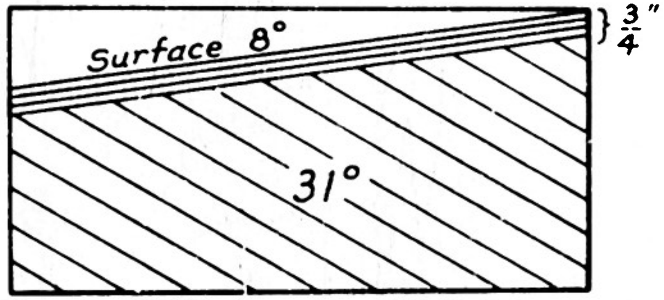



F. Location of sections 1-9.

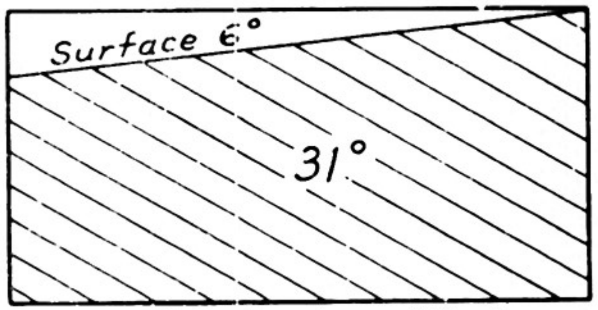
Fig. 20 - Sections of Barchan Dune, n.e. of Leupp, Arizona.
Prevailing wind from s.w. to n.e.



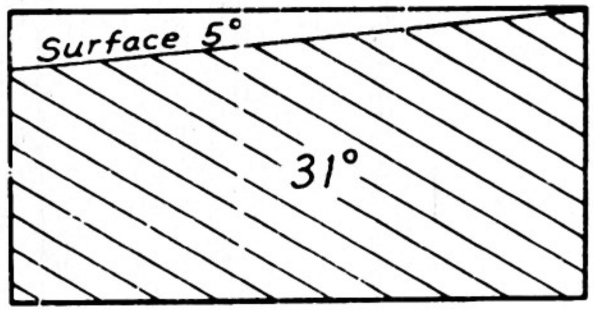

Sec. 6 - (12 ft. from base; 72 ft. from crest)




Sec. 7 - (24 ft. from base; 60 ft. from crest)




Sec. 8 - (36 ft. from base; 48 ft. from crest)




Sec. 9 - (48 ft. from base; 36 ft. from crest)

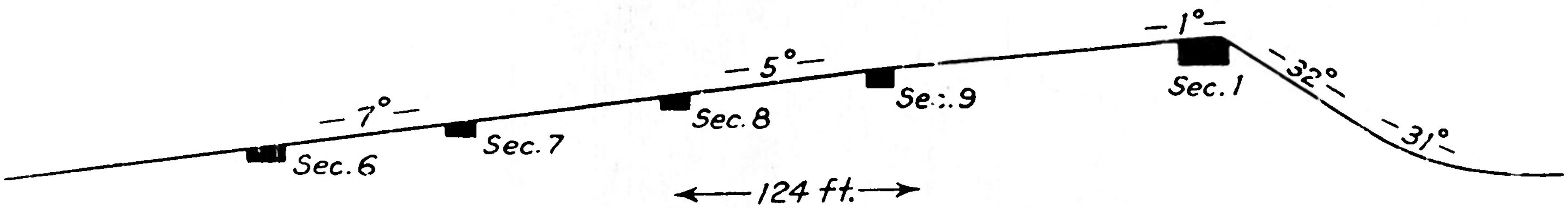



Fig. 21 - Profile of Barchan Dune take through crest in direction of dominant wind.

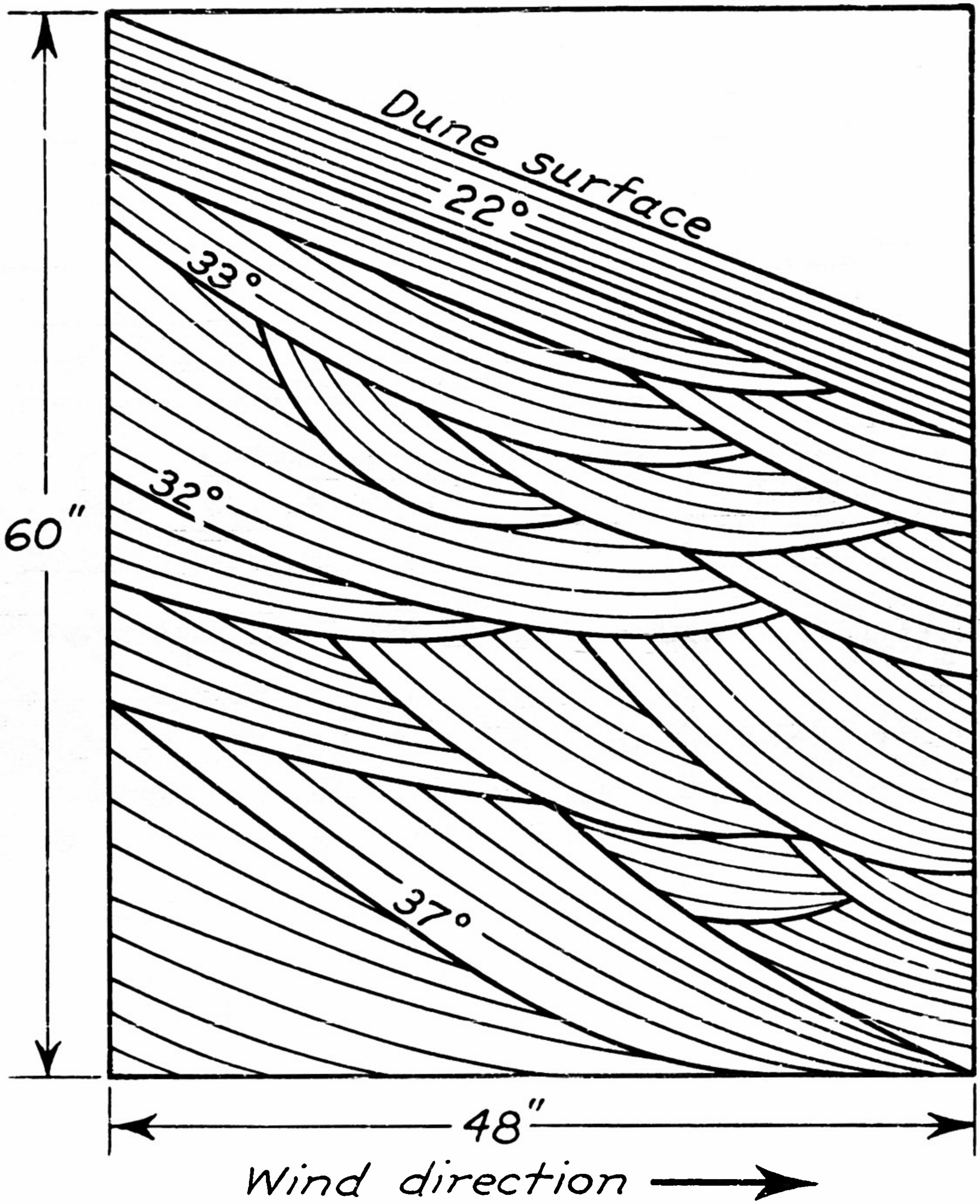



Fig. 22. - Structure in section of high dune anchored by vegetation, Station C, Mustang Is., Texas.


Plate III. - Stratification of Barchan Dune northeast of Leupp, Arizona.

A. Windward side (Sec. 6), showing steep lee-side deposits covered by gently sloping strata formed by wind driving up dune.
B. Northeast horn (Sec. 3), showing two sets of windward-side strata.
C. Crest (Sec. 1), parallel to wind direction.
D. Ridge 16 ft. s.e. of crest (Sec. 2), normal to wind direction.
E. Crest (Sec. 1), left section parallel to wind direction.

Transverse Dunes on Mustang Island, Texas

On Mustang Island, Texas, which is a large barrier between Corpus Christi Bay and the Gulf of Mexico, well-developed transverse dunes cover a large area parallel to and bordering on the beach. These dunes are formed with crest ridges that are nearly straight for distances of from two hundred to four hundred feet and are oriented with the ridges approximately at right angles to the shoreline. Along the borders of the active dunes, vegetation has anchored many dunes causing them to lose form and turn into blowouts.

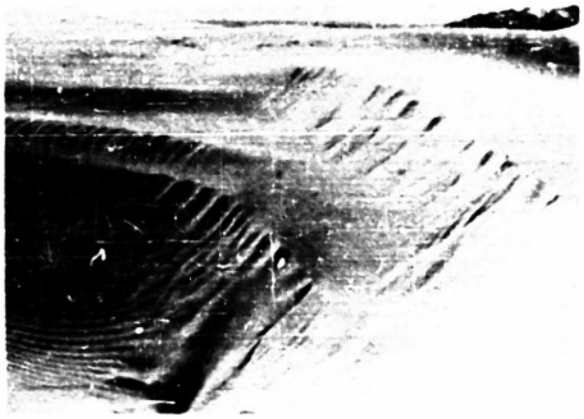
Sand forming the transverse dunes is essentially like that on the nearby beach. It is dominantly fine-grained (about 80 per cent) and has good sorting according to the classification of Payne. Measurements of dip on the windward sides of dunes vary from 7 to 15 degrees and on the lee sides from 30 to 34 degrees (Table 8). The windward sides are covered with ripple marks, most of which are oriented with crests normal to the wind direction and parallel to the dune ridges. (Plate IV b). The lee sides are marked by slumping in many places (Plate IV a,c,d).

Table 8. Degree of dip on typical transverse dunes, Mustang Island, Texas.

| | Dune #1, Height 11 feet | | | | | Dune #2, Height 5 feet | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | a | b | c | d | e | a | b | c | d | e |
| Dip Lee Side | 32° | 33° | 34° | 33° | 33° | 32° | 30° | 33° | 32° | 33° |
| Dip Windward Side | 11° | 13° | 9° | 10° | 10° | 15° | 11° | 8° | 10° | 7° |

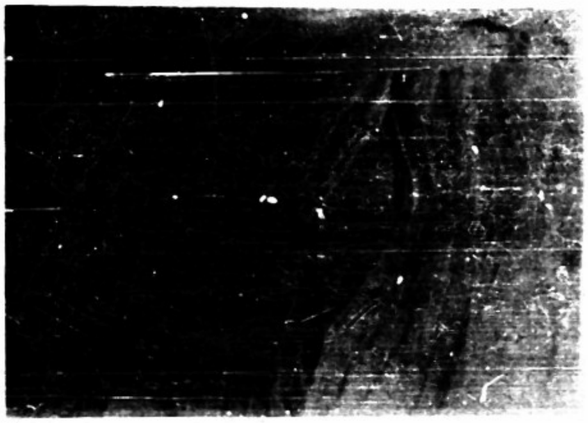
The transverse dunes of Mustang Island differ from typical barchan dunes primarily in that their crest ridges are essentially straight for considerable distances. Although their ends curve forward to a small extent as wings, the dunes do not have the form of crescents, but appear as parallel rows of nearly straight sand ridges.

Equipment was not available for saturating any of the transverse dunes so they could not be dissected to show vertical faces or analyzed for structure pattern. In a few places, however, where vegetation had anchored the sand, good sections were exposed to view showing the stratification in two dimensions. Typical samples cut parallel to wind direction are in Figure 22 and Plate IV f. A bevelled, nearly horizontal surface is in Plate IV e.



A.

B.



C.

D.

E.

F.

Plate IV. - Structures of Transverse Dunes, Mustang Island, Texas

A. Slumping on lee side of dune.

B. Ripple-marked windward surface and steep, even lee surface characteristic of dune.

C. Pattern of slump on lee side.

D. Slump marks indicated by dark accumulations of debris, lee side surface.

E. Bevelled and etched dune surface showing nearly horizontal section of transverse dune.

F. Vertical section of partially anchored transverse dune. Cut at 45 degree angle to wind direction.

## ALLUVIAL FAN STRATIFICATION

### Characteristics of Alluvial Fans

Alluvial fans are stream deposits formed along mountain fronts as a result of the tendency of streams to attain graded courses in such situations. Every fan includes (1) a fan head which is the area about the apex where the stream emerges from the mountain, (2) a middle area or midfan, and (3) a lower, outer margin referred to as the base. These features grade from one into the other downstream, but are sufficiently definite to give most fans a distinctive form similar to the segment of a cone.

Areas of bold relief are requisite to the forming of alluvial fans for only in such situations are streams sufficiently loaded with detrital material to accomplish the type of sedimentation required. Arid to semi arid climates, characterized by relatively few but violent floods and by extremes in run-off, are especially favorable but not essential to fan development. Humid-climate environments exist in some areas of extensive fan development as in the Alps and Himalayas.

Alluvial fans develop through transportation and deposition of detrital sediment by any of several distinct processes or by combinations of these. The depositing agents in these processes are listed by Blissenbach (1952), as (1) sheetfloods, (2) streamfloods and (3) streams. The sheetfloods occur where a large, concentrated volume of water and debris, acting like a viscous medium, spreads like a sheet or blanket over the surface of a fan. Streamfloods likewise are spasmodic and, where violent, resemble sheetfloods except that they are confined to definite channels. Streams develop where the water supply is constant and even, rather than concentrated and violent, and are restricted to channelways.

The internal structure, the permeability and other properties of fans are in large measure determined by the relative contributions of each of the aforementioned agents. Thus, fans differ widely from place to place and may vary within one area. Sheetfloods and many streamfloods involve a mudflow movement, resulting in deposits that are largely unsorted, unstratified and with much clay or sand matrix. In contrast, streams and relatively mild streamfloods tend to develop sorting, stratification and preferred orientation of particles.

The size and thickness of alluvial fan deposits is dependent largely on the magnitude of the mountain front that controls its development and on the mountains that furnish the detritus. Fans with radii up to forty miles have been recorded (Grabau, 1913) but such are exceptional. Many individual fans in southwestern United States are as much as five or six miles in radius but the majority range from this size down to minute examples. In many mountain fronts, series of fans tend to coalesce, thus forming compound alluvial fans or alluvial piedmont slopes of great lateral extent (Lahee, 1941). Some large fans are reported to be one thousand feet and more in thickness (Eckis, 1928, p. 224).

The surface form of any alluvial fan normally develops through a series of changes that may be considered a normal cycle of growth, related to the tendency of the mountain stream to attain a graded course. Such changes, in general, involve progressive erosion in the fanhead area and deposition down fan. Other changes in the surface character of fans are those resulting from variations in base level that affect erosion and deposition, those due to climatic change and those caused by tectonic movements. Among the more conspicuous results of such changes are superimposed fans, fans with telescoped structure (Blissenbach, 1952), and irregular structures resulting from the process of slumping.

The surface slopes of alluvial fans are, in general, slight. The angle of dip is recorded (Eckis, 1928, p. 223; Eardley, 1938, p. 1408) as less than 10 degrees on most fan surfaces and, on a large majority, it probably is less than 6 degrees (Lowson, 1915, p. 25). Dip angles on alluvial fans have been classified by Blissenbach (1952) as steep when greater than 5 degrees, gentle when between 5 and 2 degrees, and flat when below 2 degrees. Blissenbach indicates that steep angles are essentially confined to the small fans and to the upper ends of large fans. Even the greatest of these slopes, moreover, is very small compared to the normal talus slope, formed in somewhat similar situations but through the process of gravitational slide. Most talus slopes range between 10 and 30 degrees with the horizontal.

The components of alluvial fans are detrital fragments of many sizes, shapes and kinds. Coarse detrital material, classed as gravel, is the dominant type in most fans, with varying amounts of sand-sized and mud-sized particles included as matrix. In a few fans medium-sized (sand) particles are the maximum represented and, conceivably, in places where the source rock breaks down exclusively into very fine debris, fans are composed of mud-sized particles only.

Properties other than particle size also vary extremely among the rock constituents of fans. Composition which is almost entirely a reflection of source material because relatively little transportation is involved, varies according to watershed. Sorting depends on source material, type of transport and distance of transport, any one of which may have a dominant influence. The result is that some fan deposits are very poorly sorted and others are the opposite. Roundness of particles, as might be supposed, is in most places poorly developed because of relatively short transport, but Blissenbach (1952) has shown that on large fans a notable increase in degree of roundness is recognized between apex and fan base for any particular grade size. Noreworthy, also, is the not uncommon occurrence in fans of subangular and subrounded fragments.

The environment of the alluvial fan is one of unusually great complexity, yet one that should normally be recognizable in ancient deposits through a number of distinctive features if adequately analyzed. Actually, relatively few deposits ascribed to this origin have been recognized in the geologic column, especially the older part, but this lack probably is largely due to the rather unusual conditions required to bury and preserve features of relief such as must necessarily have accompanied all alluvial fans. Furthermore, as pointed out by Lawson (1913) and Barrell (1925), the bold relief necessary to produce alluvial fans probably was absent in most places during much of geologic time.

## Stratification of Santa Rita Mountain Fans, Arizona

Along the west base of the Santa Rita Mountain range in southern Arizona is a series of large alluvial fans, considered to be typical of those formed in an area of bold relief and of arid to semiarid climate. One of these fans, located near the mouth of Madera Canyon, was examined from the standpoint of sedimentary structures. A series of sections, exposed through natural erosion at various points, from one to four miles out from the fanhead, made possible the observation of many features.

Deposits of the Santa Rita Mountain fan include what appear to be several contrasting types. In places, the deposits consist of unassorted and unstratified gravels, sands and clays with individual particles ranging up to 3 feet in diameter (Plate V a,d). They are interpreted as the products of mud flows formed during times of sheet flood. Locally much of the fan is of this type. Elsewhere stratification has been developed with varying degrees of excellence (Plate V a,c ). Some involves thin layers of tongues of gravel; much of it consists of moderately well-sorted beds or laminae composed of fragments ranging from granule down to clay size.

The stratified deposits of the Santa Rita fan are for the most part irregular and lensing and dip only at low angles. In most places they are formed on gently sloping, slightly irregular surfaces of earlier, unassorted sediments (Fig. 23, 24 ) suggesting that they are the product of stream flood deposition across the fan. In other places they fill channels or troughs so appear as lenses in cross-section (Fig. 25, 26). Such deposits may have been deposited by stream floods; however, they also may be the product of normal stream-flow. Complex cross-stratification was not observed filling any of these channels, but regular, parallel strata with initial dip of a few degrees are characteristic of some channels.

In alluvial fans of the Santa Catalina Mountains, Arizona, studied by Blissenbach, (1952), some trough deposits that he described and illustrated show deposits that display typical festoon structure and other varieties of cross-stratification. It seems probable that these structures have formed from the processes of regular stream flow, rather than from flash floods. Thus, stratification in alluvial fans appears to vary greatly according to the type of types of deposit represented, i.e., stream, stream flood or sheet flood, and moy be well stratified or completely unstratified as a result.

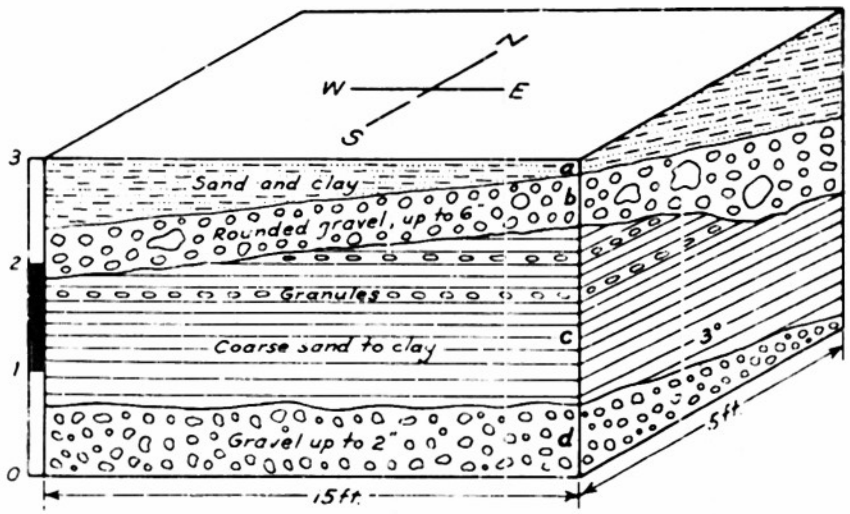



Fig. 23 - Santa Rita Mts., near Madera Canyon, alluvial fan, 4 mi. from mtn. base.

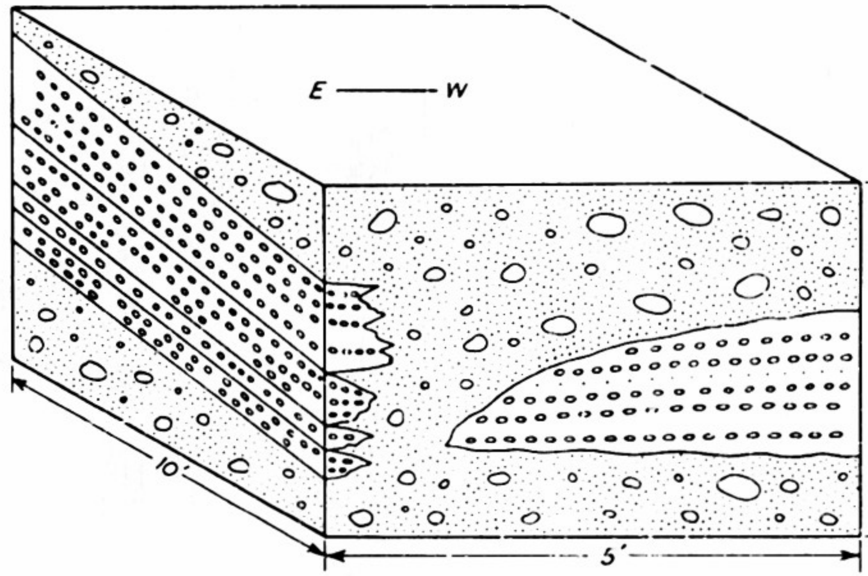



Fig. 24 - 2 mi. w. base, Santa Rita Mts., alluvial fan, near Madera Canyon.

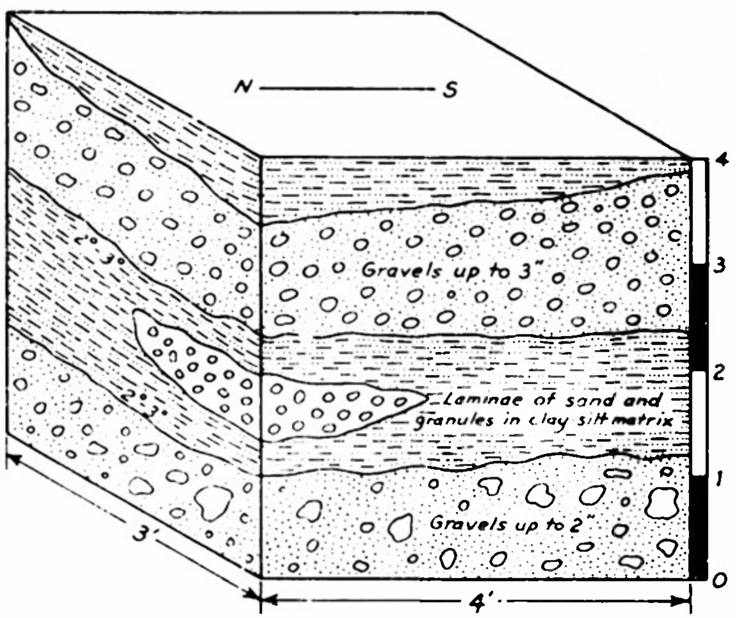



Fig. 25 - Santa Rita Mts., near Madera Canyon, alluvial fan, 1 mi. from mountain base.

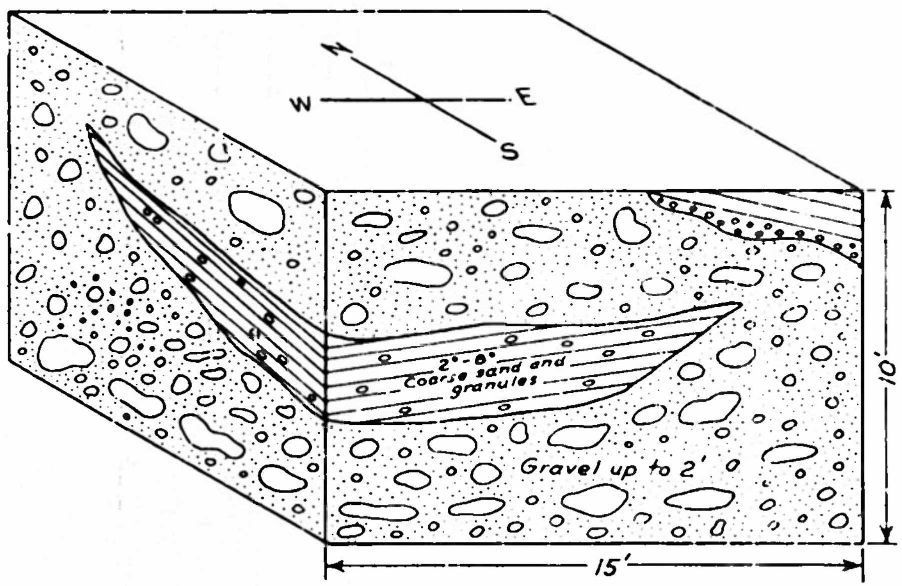



Fig. 26 - 2 mi. from base of Santa Rita Mts., alluvial fan, near Madera Canyon.

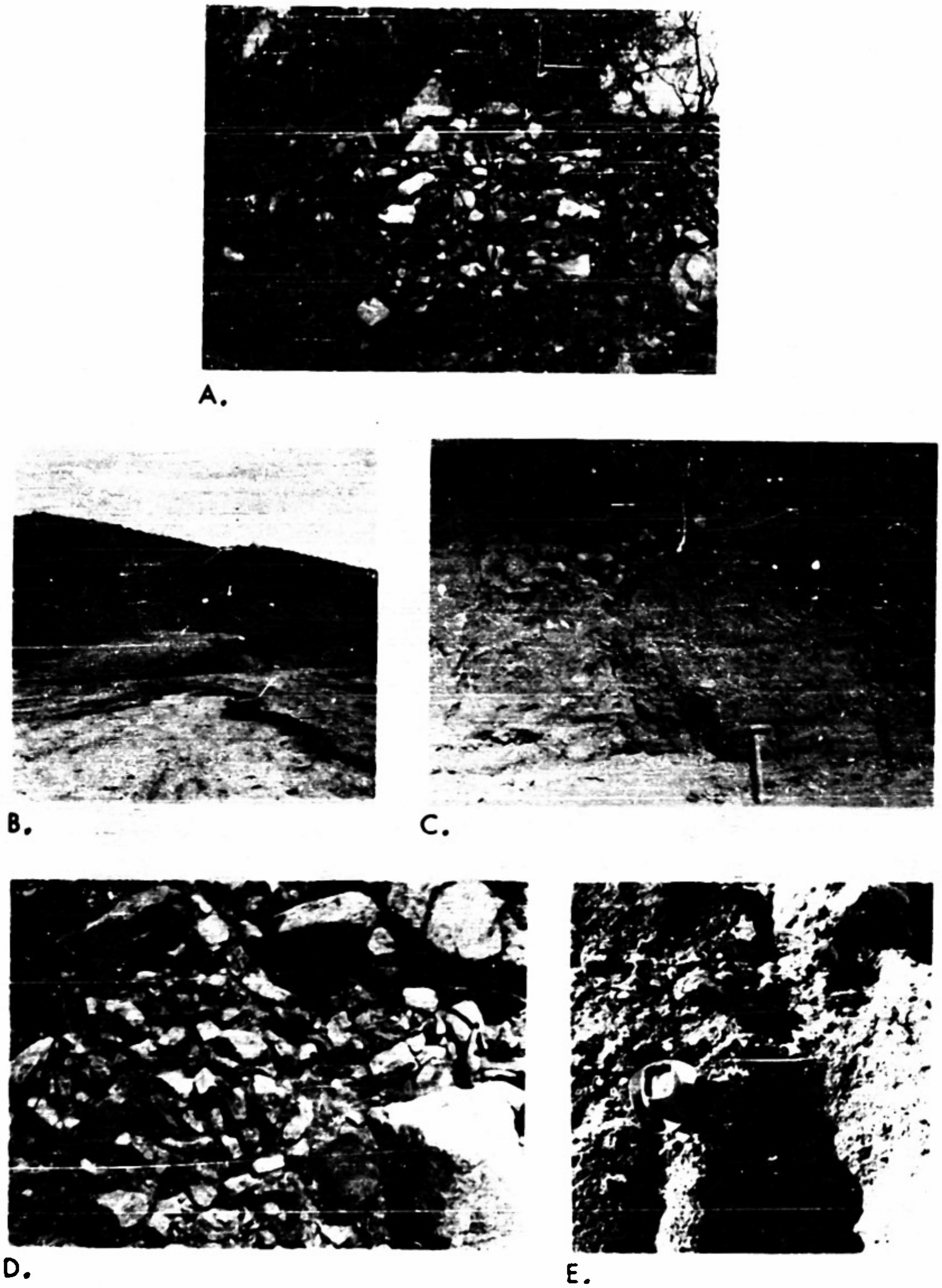



Plate V. - Stratification of alluvial fans, southern Arizona.

A. Santa Rita Mountains, Arizona. Lack of structure in mudflow-type of deposit.

B. Black Hills, near Mammoth, Arizona. Small, "telescoped" fan on larger fan. Stream-type stratification. Photo by Blissenbach.

C. Santa Rita Mountains, Arizona. Dipping gravel beds formed by stream flood deposition.

D. Santa Rita Mountains, Arizona. Unstratified, unsorted deposits of sheet-flood development.

E. Santa Catalina Mountains, in Arizona. Stratified deposits of stream-type in large fan. Photo by Blissenbach.

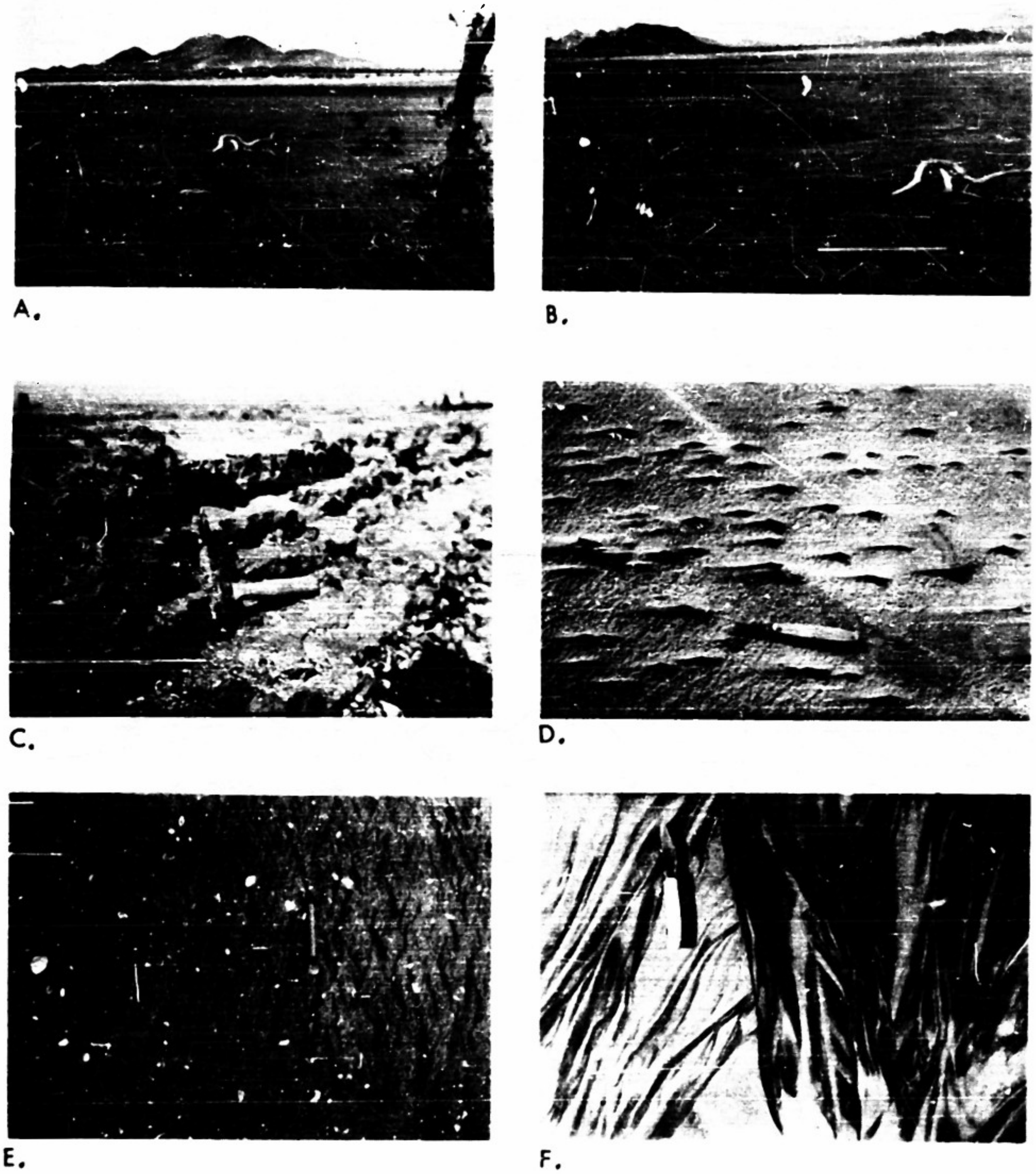



Plate VI. - Structures of Floodplains, Lagoons, and Beaches
Sonora, Texas and California

A. B. Floodplain above estuary north of Guaymas, Sonora. Red silts and clays with shrinkage cracks and salt crusts predominate.

C. Lagoon at Corpus Christi, Texas. Beds of fine sand, coquina and large mud concretions.

D. Lineation structures due to salt concentrations and subsequent wind erosion. Dry surface of lagoon on Mustang Is., Texas.

E. Backwash marks on foreshore beach. Long Beach, Calif.

F. Rillmarks on foreshore beach, La Jolla, Calif.

## LAGOON STRATIFICATION

### Characteristics of Lagoons

A lagoon is an environment of sedimentation transitional between marine and continental. It is a standing body of water, normally shallow, which is separated from the sea by a bar, spit or other barrier so that wave energy does not affect it materially. It may receive water from the sea through a tidal inlet or from occasional waves that break over the barrier; it receives fresh water from rivers or streams on the landward side. The waters of lagoons, therefore, vary from normal marine to fresh, or may become highly concentrated as in areas of considerable evaporation.

Lagoons vary greatly in size and shape, in the type of barrier that separates them from the sea and in the climatic conditions under which they develop, but they have in common a position adjacent to the sea. Sediments in lagoons may be from any of four principal sources or from combinations of these. Most commonly they are introduced by streams from the landward side and consist of detrital materials - clay and silt (Krumbein and Aberdeen, 1937) or, if in an area of marked relief, coarser fragments also. Sediments may also be introduced from the seaward side through tidal currents, exceptionally high waves, or by the wind. Another source of sediment is from dissolved salts which, in areas of poor circulation where evaporation exceeds inflow, may be exceedingly significant. A fourth source is from organisms, either invertebrates that thrive in quiet muddy waters or that float in, or plants that become extremely abundant in the late stages of lagoon-filling when swamp conditions develop.

Stratification in lagoonal deposits may be expected to consist dominantly of horizontal beds or laminae. Most of the sediments are accumulated under conditions of quiet water. Currents, except where tidal channels occur or near the mouths of streams, are relatively unimportant in most lagoons. Furthermore, the extremely fine texture of most lagoonal sediment precludes the likelihood of much cross-stratification being present. Thus it seems probable that in the interpretation of ancient rocks of lagoon environment, recognition must be based more on the composition and texture than on any distinctive types of structure. Of major consideration, however, is the relationship of the lagoonal deposits to those of adjacent environments, especially of the barriers most of which have characteristic structures.

### Corpus Christi lagoon, Texas

The great sand barrier extending along the Gulf Coast of Texas from the vicinity of Galveston to Brownsville is responsible for some of the largest lagoons on the continent. These lagoons extend almost continuously for about 300 miles and other similar ones continue far south along the Mexican coast. They are connected with the open sea by channels or passes formed at various intervals by breaks in the barrier and through these channels marine waters enter freely. Along the inner margins of the lagoons, rivers draining the flat coastal plain empty their fresh waters to mingle with the salt and they deposit loads of clay and silt.

No detailed study of primary structures in the lagoons of the Texas coast has been attempted, but random observations were made in the lagoon back of Mustang Island near

Corpus Christi. The character of the sediment and features of stratification were noted at three places: (1) on the shoreward side of the lagoon where the Neuces River enters near Aransas Pass, (2) on an island in the middle of the lagoon where the Port Aransis Causeway crosses the lagoon, and (3) on the inner shore of the barrier between the dune area and the low tide level of the lagoon.

The part of the lagoon on the landward side, near the mouth of the Neuces River is largely filled with a yellow-brown to gray, sticky mud. In places the surface is bare, marked only by the patterns of very irregular shrinkage cracks; elsewhere it is covered by mats of vegetable matter. Excavation into the clayey sediment showed no evidence of well defined stratification and it seems probable that if any once developed, it has since been destroyed by roots and cracks. One noteworthy feature of this area is an ancient channel filled with white quartz sand and broken shell fragments and marked with a few thin ( 1/4 inch) flat-lying layers of black carbonaceous matter and plant roots. Apparently currents of marine waters at one time advanced up this channel.

The island in the middle of the lagoon adjacent to the Port Aransis Causeway, is located near a major channel. It is composed largely of three- to five-inch beds of shells and fine quartz sand. In some strata, the shells form coquinas, but in others they are sparse and mixed with sand. Many of the beds locally are separated by accumulations of sandy clay balls that range from one-half inch to three inches in diameter. In one place beds of sand, alternating with others of shell fragments, dip 4 degrees to form simple cross-stratification. The shell accumulaiians, the rounded clay balls and the cross-bedding all indicate persistent, if not strong, current action in this part of the lagoon, with sediment being introduced from the barrier side.

Sand deposits forming extensive flats on the inner side of the Mustang Island barrier between an area of active dunes and the low tide waters of the lagoon are interpreted as an exposed part of the lagoon sediments. These fine sands are texturally like those of the beach and the dunes on the barrier and clearly were derived from them, but they were deposited under quiet water conditions of the lagoon. Trenches dug into these deposits show weakly-defined lamine of gray and white, dipping one to two degrees toward the lagoon. In one place, a conspicuous stylolite-like rust mark about one eithth inch wide, with straight walled depressions and ridges, was developed along a lamination surface. At another place, deposits of black and rust-colored carbonaceous matter formed a series of flatlying, parallel lenses, each 1/8 to 1/4 inch thick and 1/2 to 2 inches long as seen in the section.

Structures on the upper surface of the lagoon sands include parallel type ripple marks oriented with crests parallel to the lagoon. These apparently formed as waters drained into the lagoon. Also in these deposits are features of wind activity, most common of which are thin tear-shaped ridges, each about half an inch long, pointing in the direction of wind movement. Each ridge is a remnant of erosion, where salt crusts have protected masses of sand.

### Cholla Bay Lagoon, Sonora

Cholla Bay on the northeast shore of the Gulf of California (Plate VII a, b) is a rounded embayment approximately two miles wide and three miles long that is covered by about twenty feet of water during times of high tide, but develops into exposed sand flats during low tide. It is surrounded by land on three sides; the fourth side faces the open gulf. Other details of description are given in this report under "Beaches" and "Tidal Flats."

a.

b.

c.

d.

e.

f.

PLATE VII - Structures of Tidal Flats at Cholla Bay, Sonora

a. View north across tidal flats at stage when sea has largely withdrawn.
b. Tidal flats covered with water, south margin of bay. Granitic source of sand in distance.
c. Cross-ripple marks covering surface of tidal flats.
d. Trench in flats showing shell bed on top of fine sand stratum.
e. Parallel ripple marks formed by incoming tide. Flattened crests from outgoing tide waters.
f. Semi-cusp ripple marks covering surface of tidal flats.

Table 9. - Analyses of water samples (ppm) from Cholla Bay, Sonora.

(Determinations by courtesy of Water Resources Branch,
U.S. Geological Survey)

| | Ca | Mg. | Na-K | $CO_3$ | $HCO_3$ | $SO_4$ | Cl | Density g/mi |
|---|---|---|---|---|---|---|---|---|
| 100 yds. beyond bay in Gulf | 469 | 1400 | | | | 2,850 | 20,100 | 1.024 |
| 50 yds. from shore, 200 yds. inside bay | 488 | 1410 | 11,200 | 19 | 123 | 2,840 | 20,000 | 1.024 |
| | | | | 162 | | | | |
| Tidal pool; 1 mi. n. on traverse | 624 | 1890 | 15,000 | 23 | 108 | 3,830 | 26,800 | 1.034 |
| | | | | 155 | | | | |
| Estuary pool; E. end of bay | 545 | 1600 | | | | 3,240 | 22,800 | 1.028 |
| Lagoon pool; E. end of bay | 582 | 1740 | 13,600 | 38 | 211 | 3,480 | 24,300 | 1.031 |
| | | | | 289 | | | | |

In contrast to the northern and southern margins of Cholla Bay which are beaches, the eastern or landward margin consists of an estuary and a series of small lagoons. The estuary is the entrance to a normally dry stream bed that traverses a desert area to the east. The lagoons, mostly north of the estuary, are cut off from both the bay and the estuary by narrow sand bars or ridges.

Cholla Bay is in a region of low rainfall (probably 3 or 4 inches annually) and of very high evaporation. The waters of bay and estuary become concentrated as a result (Table 9). Slightly elevated borders of the estuary which are dry during low tide are covered with vegetation consisting of Saltwort (Bateis maratima), Salt Cedar (Monanthochloe littoralis Engelm.) and Glasswort (Salicornea sp.) - all plants having a high salt tolerance. Similar vegetation covers marginal areas of the lagoons, the waters of which also show salinity above normal.

Deposits of Cholla Bay and its estuary are composed very largely of clastic sediments, though much organic material is included as indicated by a black color in many places. They consist both of detrital sands derived largely from a granitic source, and of molluscan shell concentrations. Deposits of the lagoons are largely black silts and clays, sticky and with putrid odor. No evaporites were found among these sediments.

Stratification in sediments of the estuary at Cholla Bay, as determined by a series of trenches, is much like that on the tidal flats of the bay itself, described in the next section of this report. Weakly defined horizontal beds of brown to black sand alternate with shell beds or coquinas. The sands include many coarse fragments of quartz and feldspar and much biotite; the shells are of pelecypods and gastropods, with those of pelecypods mostly broken and fragmentary. Individual beds vary widely in thickness with a range from less than an inch to twelve or more inches.

Excavations were also made into one of the sand bars or ridges separating the estuary from a lagoon. Bedding within this bar consists of sediment similar in composition to that in the estuary, but entirely of light color. Beds are horizontal as seen in sections parallel to the ridge, but they dip about eleven degrees toward the lagoon. The coquina beds average one to one and a half inches in thickness, as compared to sand beds averaging 4 to 5 inches.

Deposits in the lagoons back of the bars are distinctly different from those of the bars and estuary for they are composed almost exclusively of very fine material accumulated under the conditions of standing bodies of water. The black sticky mud contains many shrinkage cracks and abundant holes of burrowing animals, both of which are inhabited by crabs. A few shells, some broken but others not, occur scattered through the clay. No evidence of stratification is detectable and the deposits appear to be structureless. Thus, the very black color and the putrid odor are the most distinctive characteristics of this clay.

Guaymas lagoons and floodplain, Sonora

At the narrow head of Estero Soldado, about 15 miles northwest of the town of Guaymas, Sonora, a flat valley several miles long and a mile wide, lies surrounded by low desert hills. The floor of this valley is formed of floodplain deposits that slope gently toward sea level at the estuary. Numerous small lagoons that are separated from the estuary by sand bars merge into the flood plain at its lower end.

Most of the floodplain is flat and barren and its surface appears white because of a crust of salts on the silts and clays. Along the margins of the lagoons and estuary, however, the surface is covered with a prostrate plant identified as Saltwort (Batis maritima) and a scattered growth of Black Mangrove trees (Avicennia nitida). In such areas the wet clay surface appears red, shrinkage cracks are very numerous and ripple marks are locally present. Crabs are abundant and the shells of high spired gastropods are common. A water sample, examined by Mr. L. S. Hughes, Water Resources Branch of the U.S. Geological Survey, from a lagoon in this area had a density of 1.051 (g/ml) and a high chloride content (38,300 ppm). It also showed Ca - 799; Mg - 2930; $SO_4$ - 5680, ppm.; indicating the high concentration of this water.

Deposits of the estuary are dominantly black except where shell layers occur; those of the lagoons and floodplain are red brown. A series of ten test trenches dug along a line normal to the shoreline of the estuary suggests a relationship between the water table and the color of these sediments. A trench on the inner margin of the floodplain showed the water table to be at a depth of two feet with both clay and mud layers above it having a red brown color. At the other extreme, in the saturated deposits at the edge of the estuary, where the water table is at the surface, all of the sand is black. On the sand bar between the floodplain and the estuary, the upper twelve inches of sand, standing above the water table, is red brown, but the sand below is black. Clays in the dry parts of the lagoons are red brown.

Stratification of the floodplain, insofar as observed, consists of thick (10-15 inch), horizontally deposited, beds of clay and silty clay. These beds locally contain a few mollusk shells and in some places have concentrations of gypsum crystals. Their surfaces are covered with shrinkage cracks over much of the area. Stratification in the lagoonal deposits could not be detected. The deposits consist of homogeneous clay to the depths examined which were about two feet.

## TIDAL FLAT STRATIFICATION

### Characteristics of tidal flats

Tidal flat deposits are those sediments that are transported and accumulated, primarily by the tide, on a plain bordering the sea. They may include parts of deltas, river flood plains and salt or tidal marshes, or they may be independent of such features. The fact that they are alternately covered and uncovered by the tide gives them distinctive characteristics.

The deposits of tidal flats are extensively developed only in areas where there is appreciable difference between low and high tide. Such conditions develop exclusively where physiographic features are favorable as in sheltered bays that are funnel-shaped and have gradual sloping bottoms. The mouths of large rivers are, in many places, especially suitable.

Areas notable for their high tides, in which sedimentary studies have been conducted, are the Bay of Fundy with a vertical rise in tide of from 40 to 60 feet and rarely above 70 feet (Dawson, 1891, p. 21), the Colorado River delta with a maximum high tide of about 30 feet (McKee, 1939, p. 66), the North Sea coast of Europe with rises occasionally up to 22 feet and commonly to 12 feet (Bucher, 1938, p. 727), and the Fraser River delta in British Columbia with an extreme vertical rise up to 20 feet and an ordinary rise of 7 feet (Johnston, 1921, p. 10).

The sediments that form tidal flats are of various types and come from varied sources, depending on local conditions. In flats bordering the mouths of rivers much of the sediment may come from bottomset beds in the open sea. These deposits are very fine-grained so can be lifted by the tides and returned to the land (Johnston, 1922, p. 115). Elsewhere the material may be introduced initially by longshore currents from areas where the coast is being actively eroded (Kindle, 1930, p. 8), or it may be supplied from suspended material which is being transported to the sea by streams as in the Colorado delta. In the North Sea tidal flats, according to Hantzschel (1939, p. 201), much of the sediment is derived from the reworking of Pleistocene glacial deposits on the sea floor.

Most tidal flats are formed predominantly of detrital sediments of very fine size--silt and clay. Sands composed of quartz grains and lesser amounts of feldspar and mica may occur and fragments of shells are common in some areas. The excrement of worms, pelecypods and gastropods may occur in abundance, especially among the black muds.

Detrital sediments are transported by the tides as they advance, first in channels and then by spreading out over the flats in sheet-like manner. The particles are deposited where loss of velocity causes the water to drop its suspended load and, as the receding tide waters normally are less powerful than the advancing waters, a characteristic deposit is formed at each crest tide.

The rate of accumulation of sediments on tidal flats commonly is very rapid. On some of the German tidal flats up to 10 feet of deposits are formed in a year. Similar figures are given for the tidal flats at Wash, England; 7 1/2 feet for the Bay of Fundy; 5 to 10 feet for the Fraser River. Such rapid deposition is significant for it is responsible for the preservation of black muds that are characteristic of many tidal flats and also of various organic remains such as trees in the Bay of Fundy (Dawson, 1868, p. 28) and shells of mollusks in many localities. The black color does not indicate a true organic mud because the organic content normally is less than 2 per cent; the color is due to FeS (Hydrotroilite) in a very finely divided state. Only locally in sheltered inner-most bays or on the landward sides of estuaries is the organic content likely to be extensive (Doeglas, Koning, Germeraad, 1949, p. 27).

Primary structures characteristic of tidal flats but not unique to them have been recorded for numerous areas. These include in addition to stratification, ripple marks of many types (Kindle, 1917), channels subsequently filled with mud (McKee, 1939, p. 79), intraformational, flat-pebble conglomerates (Bucher, 1938, p. 734), mudcracks (Bucher, 1938, p. 737), drag marks from seaweed, gas bubble marks and trails or tracks.

## Tidal Flats at Cholla Bay, Sonora

In order to obtain data on the character of stratification on tidal flats, examination was made of Cholla Bay (Plate VII a,b) a few miles northwest of Punta Penasco on the Sonoran coast of the Gulf of California. This bay, approximately two miles wide and three miles long, has a daily tide with vertical rise of about 20 feet. It is in a region of only a few inches annual rainfall and is enclosed on three sides by desert land. To the south are low granite hills that supply much of the sediment in the bay; to the east is a flat country traversed by a stream bed that normally is dry; to the north is a ridge of dunes separating the bay from flat land beyond.

The environment of deposition at Cholla Bay is mostly that of a large tidal flat, but a fringe of other environmental types nearly encircles the flat. Beaches border it on both north and south and, on the north, the beaches merge into dunes. An estuary extends eastward from the head of the bay and this is flanked by lagoons separated by sand ridges or bars. The deposits of all of these lesser physiographic features are distinctive and different from those of the tidal flats that they border.

Deposits of the tidal flats nearly everywhere consist of two principal types--fine sand and coquina. The sand is composed largely of quartz grains, but also contains feldspar and mica. Some of it is gray or yellow when wet, but much of it is black. Upon drying the black sand appears gray. The coquina in some places is composed entirely of shell fragments, but in others consists of concentrations of whole gastropod or pelecypod shells. In many beds sand grains and shell fragments occur mixed in varying proportions.

Mechanical analyses were made of a series of 13 samples collected at intervals along the length of the tidal flat (Table 10). The grade size distribution in these shows a maximum concentration in very fine sand for six of the samples, in fine sand for six and in coarse sand for one. Grain size therefore averages slightly coarser in tidal flat sand from Cholla Bay than in that from the Bay of Fundy as reported by Ganong (1903, p. 281) and considerably coarser than that of a typical German tidal flat as given by Hantzschel (1939, p. 199). On the other hand, the tidal flat sands of Cholla Bay are consistently much finer than most of the beach, estuary and bar deposits that nearly surround them (Table 4). None of the rounded granite gravel that forms part of the south beach occurs among the tidal flat deposits.

Table 10. - Percentage of shell matter, grade size of sand (exclusive of shells), sorting of sand (exclusive of shells). Tidal flat deposits, Cholla Bay, Sonora.

| Locality No. | Per cent shell matter | Grade size of sand (per cent) V.C. | Coarse | Med. | Fine | V.F. | Silt.Cl. | Sorting of sand (Payne scale) |
|---|---|---|---|---|---|---|---|---|
| 1a | 17.6 | 12.2 | 7.0 | 8.8 | 23.4 | 39.2 | 7.5 | Poor |
| 1b | 8.9 | 3.7 | 3.4 | 16.5 | 38.9 | 30.9 | 6.2 | Fair |
| 1c | 23.1 | 6.2 | 6.5 | 35.3 | 47.1 | 1.3 | 1.0 | Fair |
| 2a | 13.6 | 0.9 | 3.4 | 27.8 | 62.0 | 4.7 | 0.7 | Fair |
| 2b | 19.3 | 4.7 | 6.8 | 24.1 | 58.7 | 4.6 | 0.1 | Fair |
| 2c | 36.0 | 27.8 | 15.0 | 23.9 | 28.3 | 3.6 | 0.6 | Fair |
| 4 | 27.4 | 17.3 | 50.7 | 26.7 | 3.0 | 1.1 | 0.6 | Fair |
| 5a | 8.6 | 2.7 | 1.9 | 2.7 | 8.0 | 76.1 | 8.0 | Poor |
| 5b | 9.6 | 0.1 | 0.1 | 13.9 | 63.9 | 16.5 | 2.6 | Fair |
| 10 | 3.0 | 0.1 | 0.1 | 1.3 | 3.7 | 85.4 | 7.8 | Good |
| 11 | 22.6 | 1.4 | 3.4 | 7.1 | 17.6 | 66.2 | 2.8 | Fair |
| 13a | 5.9 | 0.4 | 1.3 | 5.5 | 23.5 | 62.9 | 5.5 | Fair |
| 13b | 43.7 | 20.9 | 5.6 | 8.5 | 18.8 | 43.1 | 4.4 | Fair |
| 25 | 14.0 | 7.2 | 6.0 | 8.0 | 13.8 | 40.1 | 24.0 | Poor |

Sorting in most sand samples of the flats at Cholla Bay is fair and in some it is poor, according to the scale proposed by Payne[1]. These determinations are made exclusive of the shell fragments that occur in varying proportions in a majority of samples and that result in an even poorer degree of sorting. The amount of shell material present as indicated by loss in weight through acid treatment ranges from 3 to 43 per cent in the samples tested (Table 10).

A series of test pits, spaced at intervals of 500 feet, was dug across the two mile width of Cholla Bay and another for nearly one mile parallel to its length.* The purpose was to determine the type or types of stratification. The pits averaged about fifteen inches deep and, unfortunately, could not be dug deeper because of the inflow of water from sides and bottom. In all of the sections exposed, stratification appeared as crude layers, essentially horizontal, of black sand, gray sand and coquina (Plate VII d). The layers of these materials ranged from one to ten or more inches in thickness and varied widely from one section to the next both in sequence and in thickness (Figure 27).

The most conspicuous and probably the most characteristic primary structures of the Cholla Bay tidal flat are ripple marks (Plate VIII e) that cover essentially every part of the surface. By far the majority of these are of the parallel type (Plate VIII a), ranging from 2 to 3 inches in length and averaging about 7/16 inches high (Table 11). This is the type that develops with long parallel crests and troughs as a result of sheet flood movement. Also present, but largely restricted to the channels of concentrated water movement, are the deeper cusp-type ripple with crescentic outlines (Plate VIII b). Both types of ripple marks show steep sides toward the shore, thus indicating that they were initially formed by the strong incoming tides. Bevelled ripple crests (Plate VII e) occur in some places, resulting from weaker outgoing tide waters. Small ripple crests inside the troughs of larger ripple marks and double crested ripple marks, locally present, are the result of weaker current action subsequent to initial ripple mark development. Cross-ripple (Plate VII c) and interference ripple marks occur in numerous places.

In a traverse from south to north across the tidal flat of Cholla Bay, the strike of the ripple marks was recorded at every 500 feet. Plotting the results (Figure 28), remarkably constant direction pattern is observed. In the distance of 2 miles rippled surfaces are almost continuously developed with trough and crest orientation at right angles to the direction of length of the bay. Approaching the beaches on both north and south sides of the bay, the strike of the ripple marks is deflected somewhat so that the crests and troughs are diagonal to, rather than at right angles to the strand. Thus, the entire pattern is one of a gentle curve that is convex toward the head of the bay. The countless millions of ripple marks on the surface of the tidal flat must indicate a ripple-laminated structure throughout the stratification below, but evidence of it either in etched surfaces exposed in pits or in color changes between beds could not be detected.

Additional primary structures observed on the tidal flats of Cholla Bay are the abundant, curving trails left by gastropods (Plate VIII d) and other animals and the dragmarks, many of them semi-circular, where kelp and other plant material was washed back and forth on the sand. Minature delta development (Plate VIII f) occurs where water drains off the flats into the channels.

1. Good sorting 90% of sample in 1 or 2 size grades.
   Fair sorting 90% of sample in 3 or 4 size grades.
   Poor sorting 90% of sample in 5 or 6 size grades.

* The able assistance of Dr. John Harshbarger and Mr. Tom Mullins in this investigation is acknowledged. Most of the photographs are by Mr. Tad Nichols.

Table 11. - Measurements of Ripple-marks, Choila Bay Tidal Flats, Sonora

| Samples at 500 ft. intervals, S. to N. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ripple length (inches) Av. of 10 | 2.8 | 2.3 | 2.3 | 8.0 | 4.0 | 3.2 | 3.8 | 3.2 | 3.0 | 2.9 | 2.8 | 3.0 | 2.9 | 2.9 | 2.9 | 3.3 | 2.8 | 3.4 | 2.8 | 2.9 | 2.9 | 2.6 |
| Ripple depth (inch) Av. of 3 | .19 | .50 | .44 | .88 | .69 | .56 | .63 | .44 | .44 | .44 | .25 | .44 | .50 | .38 | .44 | .44 | .31 | .50 | .37 | .50 | .44 | .25 |
| Ripple width (feet) Av. of 10 | --- | 2.4 | 2.6 | 4.8 | 4.7 | 3.1 | 2.6 | 3.4 | 3.4 | 2.8 | 2.0 | 2.8 | 2.2 | 2.4 | 2.3 | 2.0 | 2.4 | 4.8 | 3.3 | 3.5 | 2.3 | 2.2 |

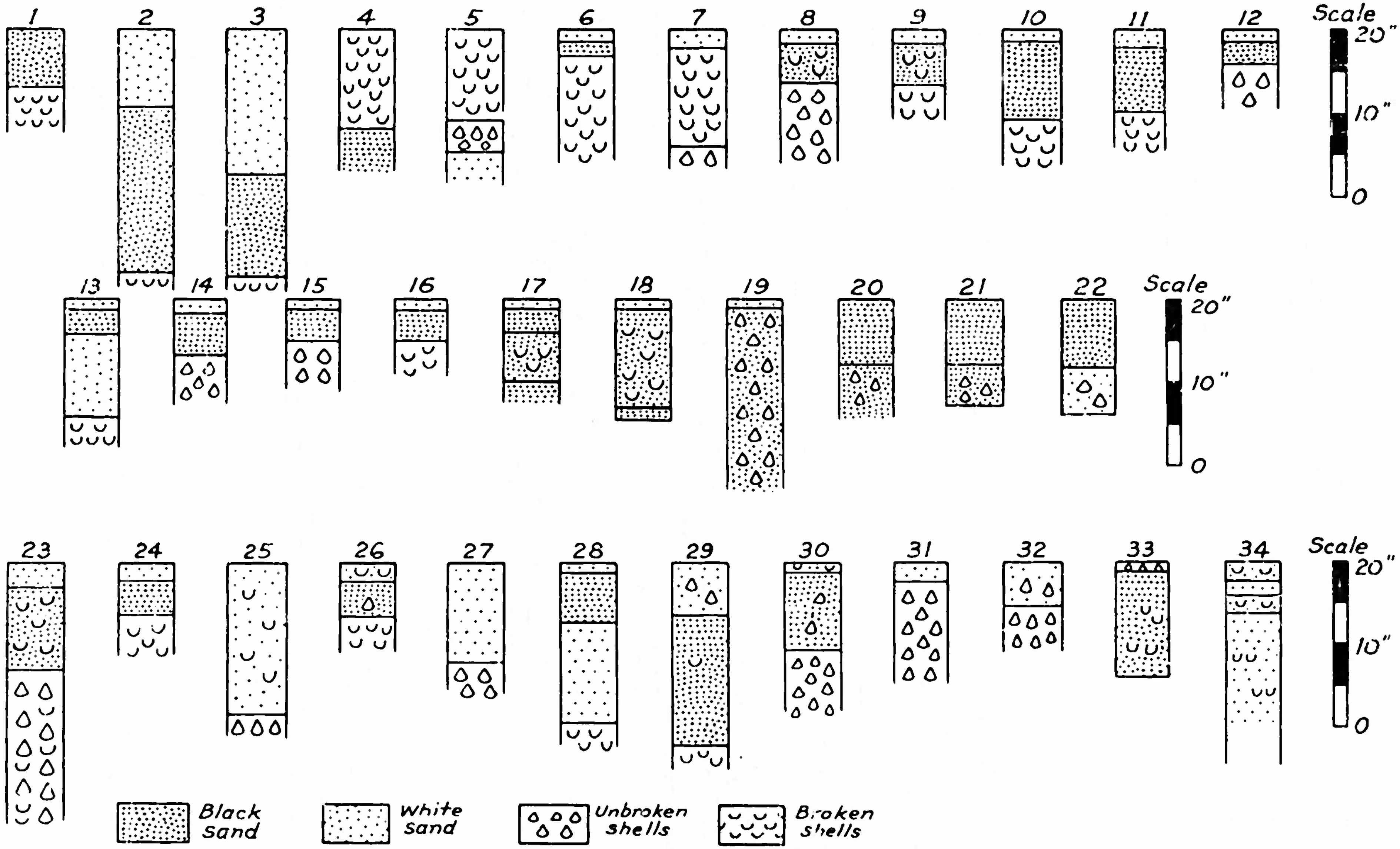



Figure 27 - Sections in tidal flats, Cholla Bay near Punta Penasco, Sonora. 1–22 series from S. to N. across bay; 23–32 series from W. to E. down bay; 33–34 estuary at E. end of bay.

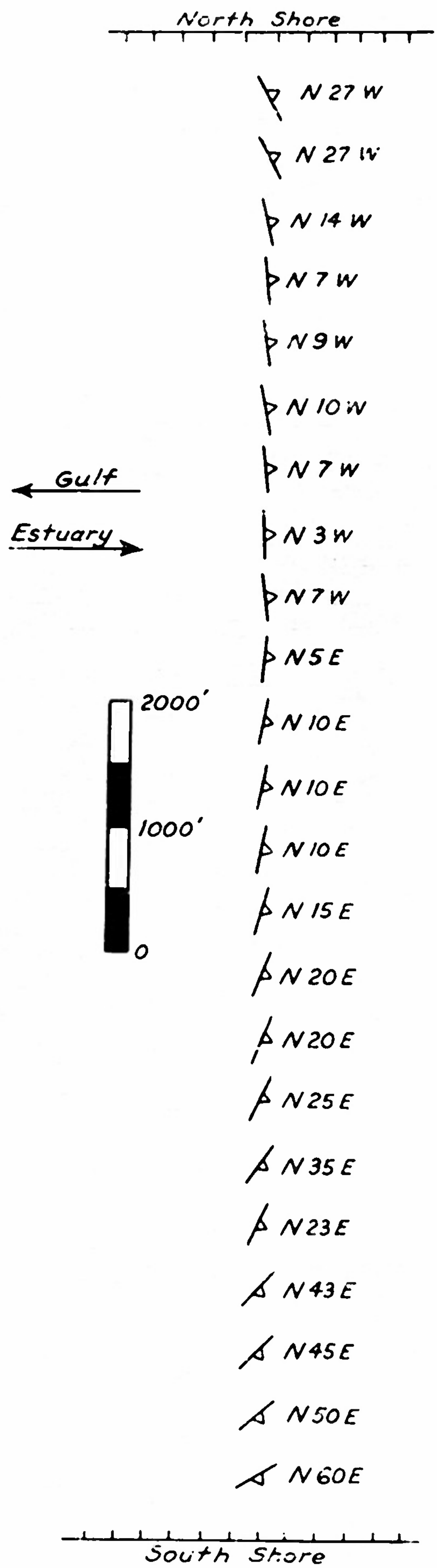



Figure 28 - Orientation of Ripple-marks across tidal flats, Cholla Bay, n.w. Punta Penasco, Sonora

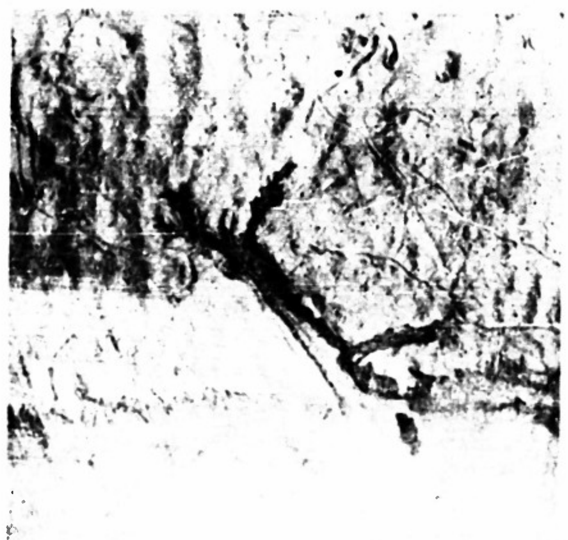
a.

b.

c.

d.

e.



f.

PLATE VIII

# EXPERIMENTAL STUDIES OF STRATIFICATION

## Character of Studies

In order to determine the causes of certain types of cross-stratification in modern sedimentary deposits, a series of laboratory experiments was conducted. These experiments had the limitations inherent in small scale and, of course, they did not include the effects of subsequent compaction represented in most sedimentary rocks. On the other hand, they offered an advantage over the study of natural deposits in that they permitted a variation of one controlling factor at a time, thus allowing the relative significance of each factor to be appraised separately.

All experimental work was done at the University of Arizona in a delta tank 5 feet long, 2 1/2 feet wide and 14 inches deep (Plate IX b). One side of the tank was constructed of glass for observation purposes and the lower end of the tank contained a series of five outlets, one above the other, to allow changes in water level at varying rates. The speed of inflow at the upper end likewise was controlled and could be measured. Water approaching the tank passed down a wide trough with gently sloping bottom where it picked up the sediment that was subsequently deposited in the tank beyond.

Experimental work was conducted by Mr. George Williams in 1950 and 1951 and continued by Mr. Charles Evensen in 1952, under the guidance of the writer. Photographs are by Mr. Tad Nichols. The work consisted of three principal phases: (1) experiments to determine the angle of repose for various types of sand and for different conditions of deposition; (2) experiments to determine types of stratification in longitudinal section formed by an agent of deposition, moving forward in a constant direction; (3) experiments to determine the characteristic patterns in cross-section where two advancing deposits were overlapping.

Numerous features of wind and stream current deposits were reproduced in the experiments. Many others could not be duplicated, largely because of inadequate equipment and insufficient time. The stream current deposits were largely restricted to types formed by laminar flow, whereas the more varied structures to be expected from turbulent conditions were not included. No attempt was made to reproduce either submarine or beach deposits which are developed by waves and by currents of other types.

## The Angle of Repose in subaqueous and subaerial deposits

Many experiments have been conducted, especially by engineers, bearing on the subject of the angle of repose of unconsolidated sediments, and a voluminous literature on this subject has resulted. One of the most recent papers, by Van Burkalow (1945), includes an excellent summary of the earlier work and presents the results of controlled experiments with carefully selected materials.

The work of Van Burkalow was restricted to subaerial angles of repose but it demonstrates that with dry, loose materials the slope of repose decreases in proportion to (1) roundness, (2) sphericity, (3) smoothness of surface, (4) density, (5) convexity in plan view and (6) degree of sorting. Her experiments likewise show that the angle of repose probably varies inversely with the size of the grains, but that the influence of this factor is relatively weak so that in natural sediments a reversal in relationship, due to the greater influence of imperfect sorting, is normal.

Table 12. - Angles of repose for sand particles in screened samples

| | | Pantano (Angular) | | | | Entrada (Rounded) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Subaerial | | Subaqueous | | Subaerial | | Subaqueous | |
| Size | Mesh | Av. | Range ≠ | Av. | Range | Av. | Range | Av. | Range |
| Granule | 10 | 37.3 | 35 1/2-39 | 34.2 | 33-36 | | | | |
| V.c. Sand | 18 | 36.5 | 35-37 1/2 | 30.7 | 28 1/2-32 | | | | |
| Coarse sand | 35 | 34.7 | 33 1/2-35 1/2 | 28.4 | 26-30 1/2 | 32.3 | 31-34 | | ** |
| Medium sand | 60 | 33.2 | 32 1/2-34 | 27.1 | 26-28 1/2 | 31.2 | 30 1/2-33 | 26.1 | 25-28 |
| Fine sand | 120 | 32.0 | 30 1/2-33 1/2 | 24.5 | 21-27 1/2 | 30.3 | 29-31 | 24.6 | 23 1/2-25 1/2 |
| V.f. sand | 230 | 31.9 | 31-33 | | * | | | | |

* Results unsatisfactory; mostly bottomset deposits

** Insufficient sample

≠ Range based on 10 independent tests

In the present investigation, the angle of repose is examined from the standpoint of its relationship to variations in slope as recorded in different types of cross-stratification. An attempt is made to determine what significance, if any, is indicated by the maximum or the average dip recorded for the deposits of a particular type. The degree of slope likewise is considered from the standpoint of any value it may have in determining the genesis of cross-stratification in ancient rocks.

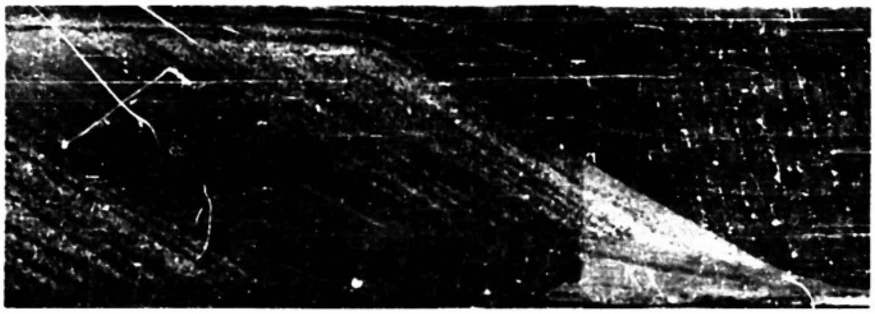
Two kinds of sand were used in these experiments. One was from the stream bed of Pantano Wash near Tucson, Arizona; the other from reworked Entrada sandstone near Fort Wingate, New Mexico. The stream sand was angular and irregular in shape; the other well rounded and uniform. For experimental purposes, both were mechanically sorted into grade sizes. These then were tested under both subaqueous and subaerial conditions and the results compared.

Data from the experiments are summarized in Table 12. They show for each type of sand a decrease in degree of dip with decrease in grain size under both the subaerial and subaqueous conditions. As demonstrated by the work of Van Burkalow, cited above, this probably is due not to differences in grain size, but rather to variations in other properties that normally are associated with size differences. Whatever the cause, a range of about 8 degrees is represented in the angles of repose for particles of comparable origin within the granule-to-fine sand size grades.

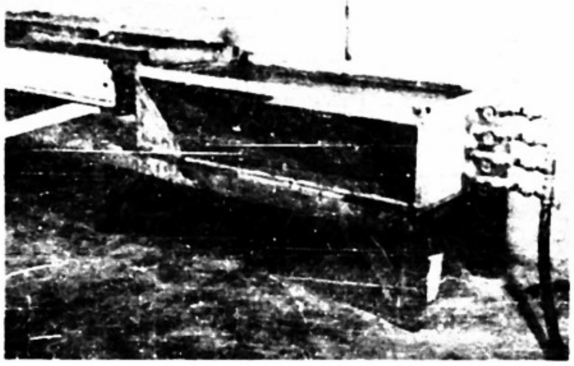
A second feature made apparent by the tests is the consistently lower range in angle of repose of the subaqueous samples as compared with that of corresponding subaerial samples. Most of the subaerial samples developed angles between 30 and 40 degrees (with the horizontal), whereas the subaqueous were between 20 and 35 degrees. The difference was especially pronounced in the lower size grades. This feature should have some significance in determining genesis when applied to the maximum angle represented or to the angle range within the majority of cross-strata, in a sandstone deposit.

Of particular significance in the interpretation of cross-stratification is the effect of clay-sized particles where mixed with sand. In dry sand they increase the angle of repose by acting as a binder and holding the mass together, but under subaqueous conditions, they serve as a lubricant and decrease the angle. Under water, furthermore, clay-sized particles mixed with sand cause the development of bottomset beds and the slopes of individual strata flatten near their bases to form tangents with the underlying surface. These curving layers are in contrast with the straight surfaces of strata formed by better-sorted sands or sands devoid of clay, in which the degree of slope at the base may be as great as that above, and bottomsets are lacking.

Experiments were conducted on the angle of repose as affected by a curving front such as might be developed by a delta lobe or a curving barchan surface. Results indicated that a slope concave in plan view was steeper than one on a straight or non-curving surface, and that a slope convex in plan view was less steep than either of the others. These results are similar to those obtained by Van Burkalow (1945, p. 687). The differences in degree of dip in all experiments were very slight, however, being a matter of only one or two degrees. Thus, the conclusion was reached that the curviature would have no recognizable affect on the degree of dip in cross-strata.



a.



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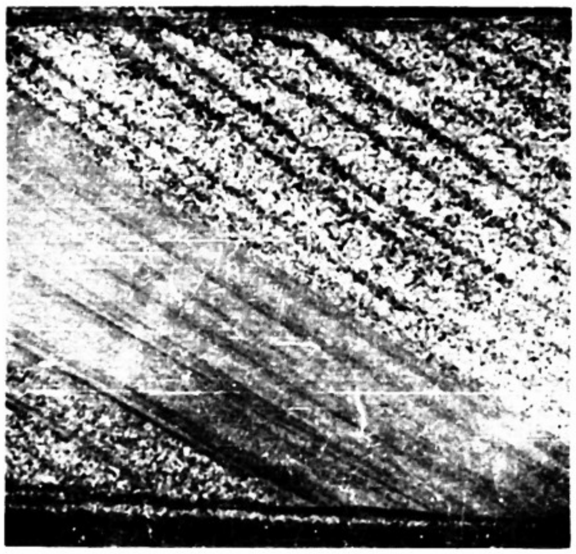


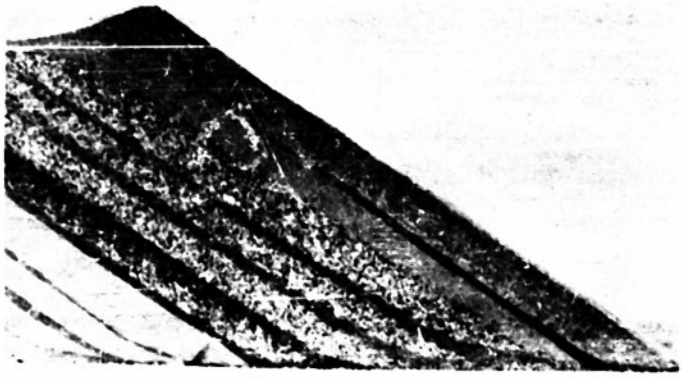
c.

PLATE IX - EXPERIMENTS IN STRATIFICATION

a. Subsets of cross-strata formed of coarse, sorted sand (left); fine sand with silt and clay (center); coarse, sorted sand (right).
b. Water tank used for experimental work.
c. Strata of fine sand with silt and clay resting on strata of sorted, coarse sand. Shows higher angle of coarse sand and partial bevelling of top stratum of coarse sand. Subaqueous.

a.

b.



c.

d.

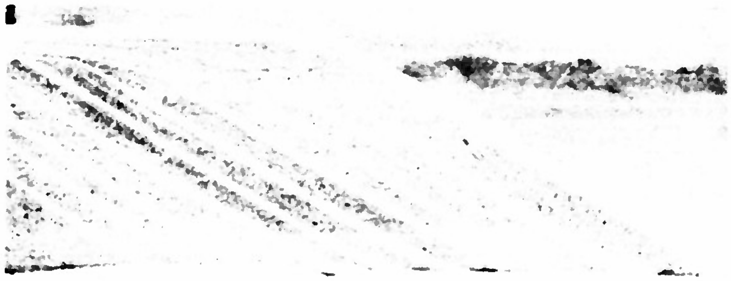


PLATE X - EXPERIMENTS IN STRATIFICATION

a. Subsets of cross-strata formed of coarse, sorted sand alternating with fine sand containing some silt and clay. Subaerial.
b. Detail view, right half of figure a, showing lower angle of dip in sorted sand (center and extreme right) than in sand containing silt and clay.
c. Subsets of angular-grained sand (left and right) separated by rounded-grained sand (center). Angular grains form higher angle. Uppermost stratum in each subset is partly bevelled. Subaqueous.
d. Same experiment as figure c, but under subaerial conditions. Note higher angles.

a. Changes in stratification due to changes in velocity. Decrease in dip of foresets and increase in amount of bottom-sets (left to right) due to increased velocity.

b. Changes in stratification due to lowering and raising of water level. Bevelled tops of foresets due to lowering water level. Series of topsets due to stages in rising water level.

PLATE XI - EXPERIMENTS IN STRATIFICATION

Cross-stratification in a standing body of water - longitudinal sections

A series of experiments was conducted in the delta tank to determine types of cross-stratification represented in sections parallel to the major direction of delta building. The character of such stratification is determined to greater or less degree by such factors as grain sorting, roundness of grain, speed of water current, and change of water level. These factors were modified one at a time, therefore, to demonstrate the effect of each. Observations were recorded and structures measured through a glass side of the tank.

In the delta experiments deposition resulted mostly in an outward advance of foreset beds. Exceptions included (1) minor erosion or deposition on upper surfaces, caused by lowering or raising of base level, and (2) limited development of bottomset beds. Because sedimentation took place in a body of standing water, deposition was accomplished largely through slumping and avalanching down oversteepened foreset slopes and not directly through current action. Most of the stratification was, therefore, of the simple type. It contrasted strongly with other types of stratification (ripple, planar, trough) which, as suggested by the studies of Illies (1949), form under various conditions of turbulent stream flow.

For the first two experiments angular, poorly sorted sand from Pantano Wash near Tucson, Arizona, was used after being mechanically graded. One size grade employed was that retained between the ten and sixteen mesh screens, termed very coarse sand. The other was that which had passed through the sixty mesh screen, defined as fine sand, but including particles of smaller grains such as silt and clay. In both of the experiments, these sands were caused to build forward as successive layers or cross-strata on the delta front.

Experiment #1 was to show the results of a change in grade size and sorting on a forward-building delta front. Using the very coarse, mechanically-sorted sand first, foreset beds having angles (with the horizontal) of 28 to 31 degrees were formed through the constantly repeated process of oversteepening at the top, followed by slumping or avalanching down the slope. Few topset and no bottomset beds were formed. With a change to fine sand, including some silt and clay, two clearly defined changes were apparent (Plate IX a, c). First, the degree of slope was reduced to between 25 and 28 degrees, with a beveling of upper portions of the earlier beds to conform to the flatter angle. Second, a prominent bottomset bed was developed at the base of each layer, causing it to form a tangent with the plane of deposition below.

Experiment #2 was a repetition of #1 except that it was done under subaerial, rather than subaqueous conditions. The results, as shown in Plate X a,b, were reversed insofar as the angles were concerned. The very coarse, sorted sand formed angles of 31 to 33 degrees (with the horizontal), whereas the fine, mixed sand ranged from 34 to 37 degrees (with the horizontal) in the dry sand. Both types developed bottomset beds, though not as extensively as in the case of fine sand with clay under water.

The results of experiments #1 and #2, involving increases and decreases in dip of beds and presence or absence of foreset development, are brought about primarily by the degree of sorting and the presence or absence of clay materials; not by changes in size grade. This feature has been discussed in more detail in the preceding section on "angles of repose."

Experiment #3 was designed to show the effects of change in roundness of grains on the development of cross-stratification. For this purpose mechanically-sieved, medium-grained sand of two types was used. One was angular from Pantano Wash, the other was rounded, derived from the Entrada formation near Fort Wingate, New Mexico. Clay and other fine particles were largely eliminated by screening in both sands. The angular was deposited first, then the rounded. Finally angular was deposited again.

The change from angular to rounded sand in experiment #3 was accompanied by a decrease in angle of dip and a development of bottomset beds. The angle (with the horizontal) in the angular sand varied between 30 and 33 degrees, and in the rounded sand between 28 and 30 degrees. The lowering of angle which accompanied the change from angular to rounded sand was initiated by a slight beveling on the upper half of the slope formed by angular sand (Plate X c ). At the same time bottomset beds were developed by the rounded sand. The reasons for this are not known.

Experiment #4 was similar to #3 but was done with dry sand. The angles attained by the sand were higher, ranging up to 36 degrees with the angular sand, but the relative amount of slope for each type was the same as under subaqueous conditions. Bottomset deposits were present (Plate X d ), but not extensive nor pronounced in either type, probably because of the rather high degree of sorting.

In experiment #5 all factors were constant except water velocity. This was increased through a series of stages of doubling the speed each time. The sediment used was medium-grained, angular sand from Pantano Wash. Starting at a rate of one gallon in four minutes, increasing to one gallon in two minutes, then one minute, one-half minute and finally one-quarter minute, a progressive flattening of the beds and an increase in the bottomsets resulted.

In this experiment, as the water velocity was increased and turbulence developed at the top of the sand slope, the sand began to flow down the entire slope rather than move down in a series of slumps or avalanches as with slow currents. Furthermore, the slope gradually changed from one with a straight even surface to one with an irregular curve. A plunge point or steep drop off developed at the top of the slope below which the angle (with the horizontal) was only 26 or 27 degrees. From this point to the bottom, the slope was gently convex (Plate XI a ) with a maximum angle of 30 degrees. The bottomset beds beyond the foreset ranged from 2 to 8 degrees (with the horizontal). All of these features became more accentuated with increase in velocity of water.

Experiment #6 was to determine the effects of change in water level. A very coarse, angular sand from Pantano Wash was used. The first phase of the experiment consisted of the uniform, forward development of foreset layers under conditions of constant water level and constant flow. Next, with a gradual lowering of water level, tops of the foresets were truncated, but new foresets continued to develop in front. Following this, a gradual rise in water level caused a new normal delta to form on the beveled surface of the older one (Plate XI b ). The new delta was developed with both topset and foreset beds. Finally, with a rise in water level slower than before, a series of topsets developed above and in step-like fashion, but no foresets or bottomsets formed (Plate XI b ).

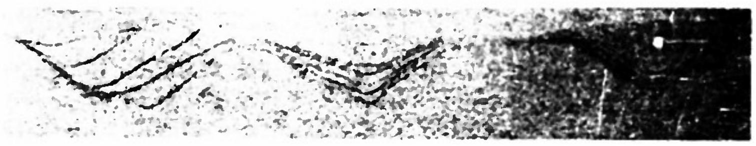
In a supplementary experiment, a rapid or abrupt rise in water level caused an exact duplication of the original uniform, forward-built foresets. The new deposits formed above the original ones as a repeated series of similar strata, giving a type of structure illustrated by Nevin (1927, p. 457) and commonly observed in some ancient deposits.

a.

b.

c.

d.



e.

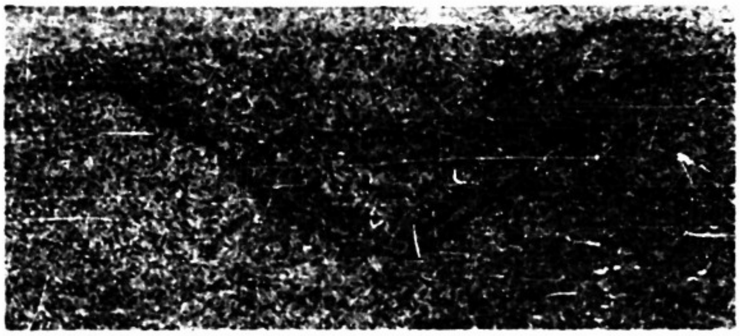
PLATE XII - EXPERIMENTS IN STRATIFICATION

a. Cross-section of multiple delta. Lobe on right built first; over-lapping lobe on left built later. Note strata are convex upward.

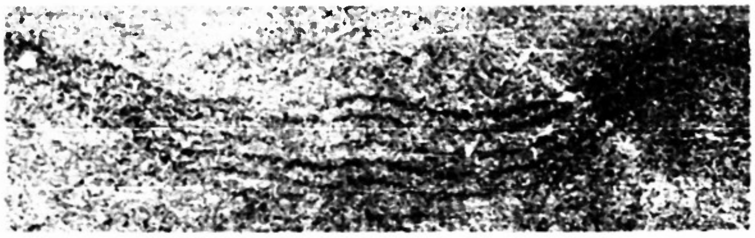
b. Cross-section of multiple delta. Over-lapping strata of right and left lobes constructed alternately. Note strata are convex upward.

c,d. Cross-sections of scour-and-fill deposits formed under subaerial conditions by streams. Note steep sides and flat-bottoms of scours, and flat-bedding that fills channels.

e. Cross-section of scour-and-fill deposits in which erosion of channels was by streams, but reshaping of channels was due to rising water. Deposition was by (left) submarine currents diagonal to channel, (center) submarine currents through channel and (right) settling from above in quiet water.

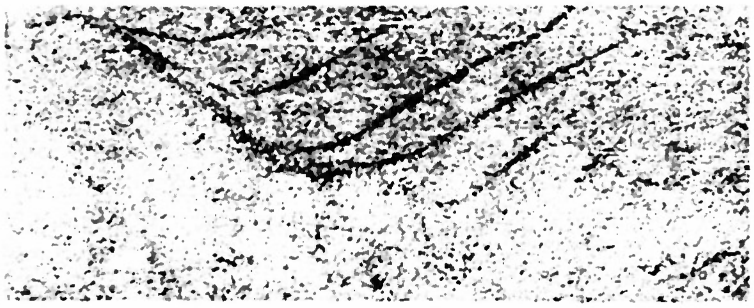


a.



b.

c.



d.

PLATE XIII - EXPERIMENTS IN STRATIFICATION

a. Symmetrically-filled channel. Scoured subaerially by stream and modified by rising water level. Strata due to settling from above in quiet water.

b. c. Symmetrically-filled channels. Thickening of strata toward bottoms of troughs. Channels formed as in (a), but filled by submarine currents through channels.

d. Asymmetrically-filled channel. Channel formed as in (a), but filled by submarine currents diagonal to channel.

Cross-stratification in a standing body of water - transverse sections

A series of experiments was conducted in the delta tank to determine the types of cross-stratification represented in sections transverse to the major direction of delta building. In such sections the structures that were formed as a result of even, forward-building, sheets of sand, deposited under conditions of slumping and avalanching down oversteepened fronts (as described in the preceding set of experiments) appear as essentially flat-lying, parallel layers. In contrast, where two or more lobes of a delta are building forward and over-lapping one another, a more complex structure results.

The first experiment in this series was one in which a delta lobe was built forward on one side of the tank and then partially over-lapped by the deposits of a second delta lobe which developed parallel to the first on the other side of the tank. In cross-section views, obtained by cutting slices transverse to the general direction of advancing delta, the strata in each lobe have a form which is arching or convex upward. The type of pattern developed is shown in Plate XII a, where the right side consists of structures of the lobe first to develop and the left side includes those of the other lobe which subsequently over-lapped the first.

In experiment #2 of this series two forward-building delta lobes again were developed, but in this experiment individual over-lapping beds were formed alternately, first from one side and then from the other. As in the first experiment, individual strata were arched (convex upward, but here they developed as a series of over-lapping layers (Plate XII b).

Cross-stratification in stream current deposits - transverse sections

Experiments on the development of cross-stratification through the activity of stream currents produced results that differ greatly from those attained in standing bodies of water such as described in the preceding experiments. Instead of deposits accumulating primarily through slumping or avalanching down foreset and bottamset planes in quiet water, sand layers are alternately scoured and filled as a result of fluctuating water currents.

In the first experiment of this series, stream currents were directed, with relatively straight courses, across a surface of stratified sand. Channels which these currents eroded in the sand were flat-bottomed, straight-walled and proportionately shallow. Subsequent filling of these channels, either through increase in stream load or through decrease in stream velocity, resulted in deposits with nearly flat-lying stratification (Plate XII b, c). In general, the stratification of the fills conformed to the flat-bottomed profiles of the scours.

In the second experiment channels were scoured in the same manner as in experiment one, but the subsequent filling of these channels was accomplished through a separate process and in a different environment. Water level was allowed to rise until the channel was completely submerged, then sediment was introduced and permitted to settle from above. Rising water in this experiment invariably caused slumping of the channel walls until they changed into curving slopes. Thus, the cross-sections of channels were altered from their original rectangular shapes into semi-circular forms. Following this, the depositing sand, settling from above, formed sets of cross-strata with semi-circular outlines conforming to channel profiles (Plate XII e, right; Plate XIII a). These are typical "festoon" patterns.

A third experiment in this series involved channel development and modification like that in experiment two, but here the filling of the channels was by submarine currents that introduced sediment from the upper ends of the troughs. Results were that individual strata developed nonuniformity in thickness, being much thinner on the limbs than in the bottoms of the synclinal structures (Plate XII e, middle; Plate XIII b, c). In other respects these cross-strata resembled those formed through settling of sand in quiet water.

In a fourth experiment, also like experiment two except for the manner of channel filling, sediment was introduced by submarine currents moving across the sand surface at an angle of forty-five degrees to the channel axes. The results (Plate XII e, left; Plate XIII d) of this type of deposition were asymmetrical "festoons".

## Conclusions

Experiments on the angle of repose of sands indicate that both subaerial and subaqueous deposits vary considerably because of differences in roundness of grain, sorting and other textural features. For any particular variety of sand, however, the maximum slope under aeolian conditions is consistently greater than that under subaqueous conditions. Furthermore, the general range for the angles of repose among subaerial deposits is appreciably greater than, though over-lapping, that for subaqueous deposits.

Experiments on the deposition of sand in a water tank illustrate features of delta deposition in a standing body of water. In longitudinal section the deposits form series of sloping strata (sets of cross-strata) of uniform character and they continue to build forward without change in form so long as environmental factors remain constant. On the other hand, even a slight change in the material being deposited (in roundness, sorting, et al.) or in the velocity of transporting agent may be sufficient to change the angle of repose and at the same time to cause local beveling or truncation of strata. This results in the forming of minor sets or subsets within the major sets of cross-strata.

In delta tank deposits formed in a standing body of water most major changes in cross-stratification result from fluctuations in water level (base level). A rise in water level will cause an original set of sloping strata to be covered (1) by a series of flat-lying topsets, if the rise is slow, or (2) by an entire new set of sloping foresets like the original, if the rise is abrupt. On the other hand, where the water level goes down, features of erosion such as beveling or scouring will develop on the top of the original set of sloping strata. The form of the resulting erosion surface will depend in large measure on the speed or turbulence of the water that is given access through change in base level.

Delta front deposits, sectioned transverse to the main direction of movement, are essentially horizonal or slightly convex upward where sedimentation has been uniform across a broad surface. In contrast, where it has involved two or more small lobes that advanced along essentially parallel lines, the stratification in cross-section forms a series of arches or upward-curving layers that over-lap one another.

Experiments involving stream erosion and deposition indicate that channels formed by water currents moving over an unconsolidated sand surface tend to have steep sides and flat bottoms and, where filled with deposits of slackening currents, contain essentially flat-lying strata. In similar experiments, where water level is allowed to rise after the channels are cut, sides of the channels slump off to form troughs with semicircular cross-sections. Where these troughs subsequently are filled through deposition while still under water, various types of festoon patterns are developed, depending upon the presence or lack of water currents and the direction of current movement where such is effective.

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